

**FINAL REPORT**

**SYSTEM FOR THE MANAGEMENT OF TRAUMA AND EMERGENCY SURGERY IN SPACE**

**NASA Grant: Number NASW-3744; Code C 40 MTDC**

**A project undertaken as a component of NASA's innovative use of the space station program.**

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**REPORT OVERVIEW:**

The original project abstract proposed the pursuit of 2 key concepts: (1) The need to develop a systems approach to the management of trauma and other major clinical medical events in space; and (2) the need to develop and evaluate appropriate hardware and techniques for the performance of surgery in space.

As regards the first of these objectives, the proposal identified the need to solicit input from clinicians and engineers with demonstrated special interest and expertise in trauma and critical care. To this end, the project helped sponsor a conceptualization and planning symposium at the Lunar and Planetary Sciences Institute in Clear Lake City on 20 and 21 July 1983. The list of participants, and the symposium agenda, are attached (Attachments A and B).

As regards the second objective, a prototype zero-gravity surgical module was constructed at The University of Texas Health Science Center at Houston and, with the cooperation of the Flight Medicine Clinic at Johnson Space Center (Dr. James Logan) and the NASA Zero-G Office at Ellington Air Force Base (Mr. Bob Williams), was tested aboard the NASA KC-135 aircraft during parabolic arc zero-G flight.

The findings and conclusions can be best organized by separately addressing these 2 phases of the project in the report that follows. The contents of the report are indexed in the outline which follows.

# REPORT CONTENTS: SYSTEM FOR THE MANAGEMENT OF TRAUMA AND EMERGENCY SURGERY IN SPACE

REPORT OVERVIEW	i
INDEX OF CONTENTS	ii-iv

## CONTENTS, Part 1: CONCEPTUALIZATION AND PLANNING SYMPOSIUM

GENERAL THESIS AND INITIAL PREMISES	1
DETERMINATION OF THE LEVEL OF CLINICAL CARE FOR WHICH WE SHOULD PLAN: VALIDITY OF USING PROBABILITY OF OCCURRENCES, AS PREDICTED FROM NAVY ANTARTICA AND SUBMARINE EXPERIENCES	4
HEAD AND NEUROLOGIC INJURIES	9
CHEST INJURIES	
IMMEDIATE CONSIDERATIONS: THE "RAPID KILLERS"	12
SECOND PASS CONSIDERATIONS: THE "LATENT KILLERS"	13
ABDOMINAL AND PELVIC IMAGING	16
CRITIQUE OF DIAGNOSTIC CRITERIA FOR SURGICAL INTERVENTION	17
PENETRATING ABDOMINAL INJURIES	19
NONPENETRATING ABDOMINAL INJURIES	20
RADIOGRAPHIC STUDIES	22
DECISION FOR IMMEDIATE CELIOTOMY VERSUS EARLY RECOVERY TO EARTH	23
GENITAL-URINARY TRACT INJURIES AND EMERGENCIES	26
CRITIQUE OF DIAGNOSTIC CRITERIA	27
IMMEDIATE CONSIDERATIONS: URINALYSIS, BLADDER CATHETERIZATION	27
RADIOGRAPHIC STUDIES: IVP	29
Kidney	30
Ureters	31
Bladder	31
Urethra	31
NON TRAUMATIC UROLOGIC EMERGENCIES	32
LIMB INJURY	34
DIAGNOSTIC CRITERIA	34
INITIAL MANAGEMENT	36
CRITIQUE OF DIAGNOSTIC CRITERIA AND INDICATIONS FOR SUBSEQUENT STUDIES	
Skeletal Injury	37
Tendon and Peripheral Nerve Injury	37
Vascular Injury	38
FRACTURE MANAGEMENT	40
PERIPHERAL VASCULAR INJURY MANAGEMENT	41
TENDON, NERVE, AND SOFT TISSUE INJURY MANAGEMENT	42

ORIGINAL PAGE IS  
OF POOR QUALITY

THERMAL AND ELECTRICAL BURN INJURIES	43
CLASSIFICATION AND TRIAGE DECISION	43
TIMING OF TRANSFER	45
RADIOGRAPHIC IMAGING	47
EQUIPMENT: CHARACTERISTICS DESIRED; DEVICES AVAILABLE	47
PRIORITIZATION OF IMAGING MODALITIES	49
Plain x-ray	49
CT	50
Digital Angiography	50
Ultrasound	50
Nuclear Medicine	50
NMR	50
ROLE OF THE RADIOLOGIC CONSULTANT	51
CRITICAL CARE	52
PHYSIOLOGIC MONITORING	55
SELECTION AND DEVELOPMENT OF CLINICAL LABORATORY EQUIPMENT	58
ISFET DEVICES	58
COMPUTERIZED DATA ACQUISITION, MANAGEMENT, AND CLINICAL DECISION MAKING	62
MEDICAL DECISION MAKING APPROPRIATE FOR REMOTE POPULATIONS IN SELF-CONTAINED ENVIRONMENTS	65
SUMMARY, CONCLUSIONS, RECOMMENDATIONS (PART 1)	69
CLINICAL MEDICAL SPECIALTY AND BIOENGINEERING ADVISORY COMMITTEE	69
COMPONENTS OF THE SYSTEM: NEED FOR ADEQUATE LEAD TIME	69
MEDICAL CREW MEMBERS: DERIVATION OF ONBOARD SURGEONS	70
DEVELOPMENT OF APPROPRIATE MEDICAL EQUIPMENT	70
DEVELOPMENT OF APPROPRIATE COMPUTER SOFTWARE AND HARDWARE	71
CLINICAL SPECIALTY CONSULTATION RESOURCE NETWORK	72
THE MANDATE FOR APPROPRIATE CLINICALLY ORIENTED RESEARCH AND TESTING	75
THE QUESTION OF COST VERSUS VALUE OF CLINICAL MEDICAL CAPABILITY	76



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CONTENTS, PART 2: APPARATUS AND TECHNIQUES FOR PERFORMANCE OF  
SURGERY IN ZERO-G.

INTRODUCTION; STATEMENT OF REQUIREMENTS AND ANTICIPATED PROBLEMS FOR INTENDED SOLUTIONS	1
BASES FOR INTENDED SOLUTIONS	
RETENTION SYSTEM FOR THE SURGEONS	4
MEDICAL SUCTION SYSTEM	4
TESTING THE APPARATUS AND TECHNIQUES	5
THE APPARATUS	
ZERO-G SURGICAL MODULE	
Size Constraints, Modularity	7
Assembly	9
Surgical Apparatus	11
Surgeon Restraint System	14
ZERO-G SUCTION UNIT	
Background	18
Construction and Function	20
TESTING THE APPARATUS: PRELIMINARY RESULTS	
LABORATORY TESTING, ONE-G	
Zero-G Surgical Module	24
Zero-G Suction (FAST SLING) Unit	25
FLIGHT TESTING, ZERO-G	
General	25
Zero-G Surgical Module and Surgical Techniques	26
Surgical Suction (FAST SLING) Unit	30
PRELIMINARY CONCLUSIONS	32
GENERAL RECOMMENDATIONS	33
ATTACHMENTS	
A. Roster of clinicians and bioengineers attending conceptualization and planning symposium, Clear Lake City, Texas 20 and 21 July 1983.	
B. Agenda, conceptualization and planning symposium.	
C. Copy of article by Trunkey DD: Trauma. Scientific American 1983; 249(2): 28-25.	
D. Copy of article by Mutke HG: Equipment for surgical interventions and childbirth in weightlessness. AA:1979; 807:1-5	

**PART 1**

**CONCEPTUALIZATION AND PLANNING SYMPOSIUM: SYSTEM FOR THE  
MANAGEMENT OF TRAUMA AND EMERGENCY SURGERY IN SPACE**

**GENERAL THESIS AND INITIAL PREMISES**

To date, clinical medical orientation in the space program has been largely preventative and diagnostic, with emphasis upon rigorous screening of astronauts to eliminate preflight disease states, use of redundancy to create failsafe life support environments to prevent inflight disasters during short missions, close interval inflight and postflight monitoring to detect acute physiological changes, and, on most missions, willingness and ability to rapidly return to earth should an untoward event occur. These factors have obviated the need for onboard medical specialty expertise. However, the development and construction of a space station or lunar base will likely imply the participation of less rigorously screened individuals, longer mission intervals, discontinuous inflight monitoring, and inability to rapidly or conveniently recover to earth at an arbitrary time. These factors increase the probability that future space flight participants will experience a broader spectrum of the medical problems affecting the earthbound, and, in turn, increase the potential benefit of onboard presence of clinical medical capability.

Extrapolation from terrestrial experience (Attachment C) suggests that, of common medical problems, trauma and emergency surgical situations represent those statistically most likely to do all of the following: (1) affect relatively young, otherwise generally healthy persons; (2) result in permanent disability or loss of life if not successfully managed; and (3) force an abrupt return to earth at an inconvenient time if satisfactory onboard evaluation and management are not possible. Either of these latter two events are almost certain to generate undesirable operational, economic, and political consequences, particularly in an effort as highly visible as the space program. It is therefore proposed that there be developed a capability for the onboard evaluation and management of major trauma and the performance of emergency surgery in space.

The development of this capability may represent NASA's first venture into the coordination of ongoing delivery of clinical specialty care, in contrast to more fundamentally oriented biomedical research activities. Embarking upon this venture, the following observations will probably be of importance:

1. In the highly visible environment of a space station or lunar base, the standards of performance of clinical medicine will be as much subject to determination by national clinical medical societies as by NASA operational medical considerations.

2. To maintain credibility with the medical community, a

decision to develop a surgical capability in space implies the need for participation of fully trained, certified surgeons in both the planning and delivery of surgical care.

3. Prior to permanent presence of relatively large numbers of people, it is hoped that careful preventative planning will result in a minimal need for and incidence of surgical procedures in orbit. Nevertheless, the ability to perform surgical procedures, should the need arise, will be increasingly important as manned orbital activity increases.

4. Maintenance of competency in surgical procedures requires regular performance of surgical procedures. Anticipating that, if things go well in the early years, a surgeon in orbit will infrequently practice surgery, the presence of a competent surgeon in orbit implies the assignment, on a rotational basis, of surgeons who otherwise practice surgery in a terrestrial environment.

5. For that reason, just as NASA is looking to the aerospace community outside the agency for ongoing management of shuttle and satellite operations, so it will be appropriate to look to the medical community outside the agency for the surgeons, other clinicians, and biomedical engineers to assemble the cadre of expertise needed to develop and deliver clinical care in orbit.

6. In definition of needs, it will be of major benefit to carefully study evolved emergency medical services systems guidelines and successful trauma programs (particularly those incorporating integral triage and transport components). Appropriate adaptations, modifications, and linkages should prevent both omission of crucial elements and inefficient rediscoveries and duplications.

7. Despite the relatively predictable and self contained environment projected for a space station or lunar base, it will be impossible to plan for every medical contingency or emergency; this suggests the benefit of immediate access by the onboard physician(s) to consultation from a network of clinical specialty physicians and bioengineers on earth. Space station implies a continuous presence in space; yet it will be impossible (certainly unrealistic) to have a variety of content experts continuously available near mission control. Therefore, it must be possible to contact the participating specialty experts at their usual sites of practice, by equipping those sites with appropriate communication and data transfer hardware and software.

8. Unfortunately, NASA physicians' previous experience with input from clinical specialty experts has sometimes been that of disappointment with the inappropriateness of suggestions offered relative to the realities of the unique operational environment with which NASA must deal in space. This experience implies the need to establish a mechanism by which NASA can provide, to both

crew member and consultant clinicians, recurrent orientation to and familiarization with this unusual environment within which medical problems may need to be handled in space.,

9. As regards ability to provide effective orientation, the question eventually arises as to the propriety of training an operational medical expert to do some surgery, versus orienting a surgeon to the operational medical environment. Observations (1) and (2), plus the usual relative lengths of formal training, argue for the latter, particularly if full surgical capability is (eventually) intended.

10. The propriety of developing full surgical care capability is influenced by a number of factors, including what kinds of injuries and illnesses are possible and probable, the costs of preparing for these, the consequences of not being able to manage these problems onboard, technical considerations related to their management, and availability of monitoring, imaging, and laboratory capabilities sufficient to confirm diagnoses and guide therapeutic decisions. To addressing these issues, a significant portion of the symposium was directed.

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**DETERMINATION OF THE LEVEL OF CLINICAL CARE FOR WHICH WE SHOULD PLAN: VALIDITY OF USING PROBABILITY OF OCCURRENCES, AS PREDICTED FROM NAVY ANTARTICA AND SUBMARINE EXPERIENCES**

From a standpoint of economics, it has been suggested that preparation for management of clinical medical problems in space should be contingent upon probability of occurrence. It has also been suggested that a good predictor of probability of occurrence of medical events in isolated populations is the Navy antartica and submarine experience.

In the Navy experience, the incidence of surgical problems has been relatively low. For example, in 21,000 Polaris submarine man-years, there were 11 pneumothoraces, 70 cases of appendicitis, 23 burns, 34 fractures, 39 ureteral calculi. In the antartica, upper respiratory infections, gastrointestinal disturbances, and dental problems constituted a majority of the complaints. Dental problems accounting for as many days lost from work as any other cause, despite all personnel being "class 1" dental status on assignment. In the Australian antartic experience, of 7200 presentations for medical care, 35-40% were for trauma. Most of the trauma was minimal. Non operative treatment of appendicitis resulted in slightly less morbidity than operative management.

It has further been suggested that the probability of major trauma and burns will be reduced in space because of absence of weight of colliding objects, and difficulty sustaining an open flame in the absence of gravity dependent convective removal of combustion product gases to allow the flame assess to oxygen.

However, it was the consensus of the symposium that these are weak agruments against planning to develop full emergency surgical capability, for a number of reasons:

1. It is anticipated that many space station personnel may be in the 40 and 50 years of age groups, in contrast to the majority of Navy personnel in the mid 20s.

2. While objects of potential collision hazard may have no weight in zero G, they have mass. Once accelerated, that mass can deliver a crushing or lacerating blow; yet, without weight, there actually may be reduced perception of this hazard.

3. While it may be difficult to sustain an open flame front, it is anticipated that explosion, flash, chemical spill, and electrical current will be forms of burn injury more commonly experienced in space.

4. The potential of construction in space introduces most of the usual risks associated with the job completion mindset in that industry, aggravated by a very unusual environment.

5. It is of interest to note that in the Navy antartica experience, many of the accidents resulting in injuries were

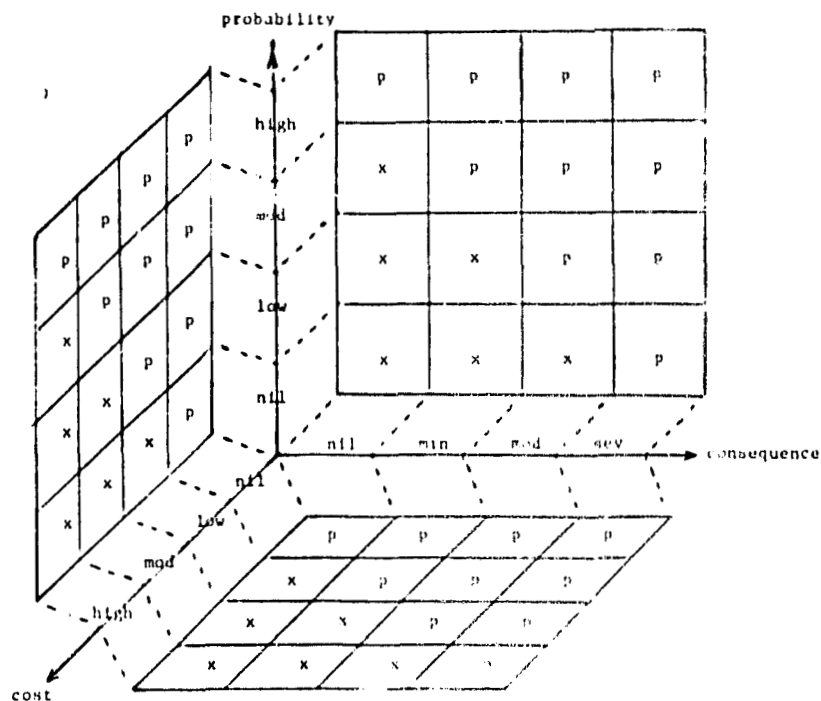
related to recreational activities! It seems unlikely that the adventurous personalities of early space travelers will be devoid of a proclivity to "horseplay."

6. While the U.S. Navy and the Australian antartica experiences have yielded apparently low incidences of benefit of surgical capabilities, another ongoing study of a remote population, that served by the Australian "outback" flying surgeons, has concluded that surgical capability, particularly for trauma, is of significant benefit.

7. Consideration of the probability of occurrence, versus the cost of preparation to successfully deal with an event, constitutes only one set of axes in 2 dimensions as regards appropriate medical planning decision making process. Another axis, of equal or greater importance, is that of the consequences: medical, operational, financial, and political, of an occurrence which cannot satisfactorily be managed onboard. If these consequences are severe, then it will pay to plan to be able to manage even some relatively improbable events:

probability of occurrence					
	high	plan	plan	plan	plan
	moderate	x	plan	plan	plan
	low	x	x	plan	plan
	nil	x	x	x	plan
		nil	minimal	moderate	severe
		consequence of occurrence			

At least 3 axes must be considered in the decision making process (other axes may be involved; the scales on the various axes may be of different magnitudes).



The "solid" defined by intersection of the projected decision boundaries can be thought of as defining a decision state space: The volume of the "plan to manage" space is determined by the criteria for establishing the boundaries between the "plan to manage" versus "omit planning" portions of each plan. In medicine, when there is doubt introduced by incomplete data, the accepted modus operandi is to error toward planning to manage.

8. As an alternative to medical management onboard space station, some NASA engineers have proposed a Gemini style reentry capsule as a Module Orbital Space Escape System (MOSES) with which to evacuate a casualty to the surface of the earth, possibly accompanied by an attendant. It is unlikely the clinical medical community will accept the MOSES concept as a solution to most medical emergencies for several reasons:

a. For many critical problems, the anticipated recovery time frame of about 2 1/2 hours from low earth orbit and 6-8 hours from geosynchronous earth orbit, assuming rapid recovery of the capsule from the ocean, will be judged unacceptable.

b. For many non critical problems, the potential risk of a mishap during reentry and capsule recovery will be judged greater than that of onboard management.

c. Most physicians will be unwilling to refer a sick patient to the Indian Ocean if there is any way they can personally maintain control.

d. If a non medical attendant goes along, minimal care can be maintained during recovery. If the doctor goes, the rest of the station personnel may be without care.

e. Using MOSES as an excuse to eliminate medical diagnostic capability will increase probability of an evacuation which would be unnecessary if extent of injury or illness could be reliably verified.

f. The ability to treat onboard may prevent many non critical problems from becoming critical.

g. Returning crew members to work, as well as protecting their health, should be primary objectives, rather than evacuation.

9. Like professional athletes, astronauts have been willing to accept unusual risks of personal injury in the course of their work. However, also like professional athletes, once injured or ill, it is likely astronauts will be satisfied only with the best medical care.

10. While it might be possible to both justify and keep low profile the morbidity or mortality suffered by a young sailor who receives non operative treatment of surgical disease while on submarine patrol in sensitive waters, it will be possible to do neither for prominent figures who probably will visit space station as public representatives and spokespersons. Members of the media are obvious examples of such visitors.

11. With reluctance to evacuate except under conditions of adequate care enroute, and need to treat certain problems immediately even if evacuation is subsequently necessary, the safest, most versatile, most acceptable, and therefore most likely evacuation vehicle will be the next shuttle orbiter. With anticipated scheduled shuttle cycle intervals of up to 21 days, and a demand by crew members, physicians, and the public for state-of-the-art medical care, the inability to adequately diagnose and treat onboard space station while waiting for the next scheduled shuttle "bus" could well force early emergent launch of an orbiter to act as an "ambulance". With costs per shuttle of \$100-200 million, a significant amount of planning for onboard diagnosis and treatment can be justified if only a single immediate ambulance run can be deferred in favor of a subsequently scheduled bus trip.

12. Cost is not the only factor discouraging an unscheduled shuttle launch: The risk, albeit low, to the healthy shuttle crew must be weighed against the risk of delaying the recovery of a space station patient in apparent need of



evacuation. Onboard ability to both accurately diagnose and reliably provide interim support will facilitate much more precise evaluation of risk versus benefit of immediate versus delayed recovery. In the absence of accurate diagnostic and adequate treatment modalities on board, the decision is much more likely to swing toward emergent recovery.

In summarizing this discussion, Dr. Donald Trunkey, representing both the American College of Surgeons Committee on Trauma (he is chairman) and the American Institute of Biological Sciences panel to peer review and advise priority of research projects proposed for space station (he is the ACS representative), unequivocally stated that it is important that we plan now to develop full capability to perform surgery and deliver emergency medical care in space. Neither astronauts, nor physicians onboard or on earth, nor the public at large are likely to settle for less. While implementation of necessity will be a phased-in process, to plan for other than full capability would be "foolhardy." In addition to cost and consequence considerations already discussed, excellent medical care is important for morale, esprit de corps, and operational success.

Dr. Trunkey also cautioned against ignoring the potential military needs as regards emergency surgical care. Historically, after frontiers have been opened by explorers, "soldiers" have preceeded construction workers and settlers.

## HEAD AND NEUROLOGIC INJURIES

In planning for evaluation and management of head injuries, it will be convenient to utilize a categorization such as mild, moderate, and severe. Mild bumps on the head may be one of the more common traumatic events experienced in zero-G. Fortunately these events should rarely progress to serious problems. Severe head injuries, such as might be sustained near an explosion, may well be fatal. Head injury is one of the most common contributors to death from blunt trauma in the U.S. today. It is of interest to note that the most common place to die from a head injury is at the site of injury, not in a hospital.

Benefitting from early surgical intervention in the mild category may be scalp lacerations, particularly with significant hemorrhage, and open depressed skull fractures in conscious patients. These are problems for which relatively straight forward surgical procedures can almost certainly make the difference between normal recovery and disaster. Capability for suturing scalp lacerations, and elevating and closing open skull fractures, should be provided on space station.

Closed head injury can be loosely categorized as primary, resulting from acceleration-deceleration forces transmitted to the brain as a whole at the time of impact, and secondary, resulting from diffuse swelling, focal hemorrhage, or infection, which may develop in injuries which initially were not so severe. Dual goals in management of head injury are to ensure favorable circumstances for recovery from primary brain damage and to recognize any secondary accident early enough to minimize its damage. Thus it is important to establish a baseline as soon as possible in order to distinguish secondary events from initial injury.

In moderate to severe head injury patients who reach hospitals, there is need for surgical intervention only about 10% of the time. Therefore, while the technical demands of craniotomy onboard space station may (initially) appear prohibitive, the probability is also low of sustaining an injury which would benefit from emergent craniotomy. On the other hand, the probability is not so low of sustaining a head injury which would benefit from careful nonoperative management. Appropriate nonoperative management or/and timely recovery to earth for further treatment may make the difference between life and death, or between normal recovery and permanent disability.

Timeliness and accuracy of decisions regarding nonoperative management of head injuries has become proportional to accuracy of monitoring and imaging modalities. Minimally invasive techniques such as Richmond bolt or ventriculostomy catheter intracranial pressure monitoring, and jugular bulb venous blood gas monitoring, are valuable aids, and should be possible to accomplish in space station setting. Distinction of diffuse swelling from focal hemorrhage or occlusion of outflow of a

ventricle is likely to continue to require a means of imaging.

Computerized tomography (CT) represents the state of the art in brain imaging today, with nuclear magnetic resonance (NMR) on the horizon, promising to offer an order of magnitude more information. Current generation machines are costly, heavy, bulky, and have high power requirements. However, as discussed in more detail in the section on "diagnostic radiologic capabilities," even without the impetus of space station it is anticipated that major breakthroughs in reduction of cost, weight, size, and power requirements of medical imaging equipment will be realized in future generation devices. This may occur at the expense of need for additional computer assisted reconstruction of images, but with the ability to locate computers remotely and telemeter data bidirectionally, this should not be a significant penalty as regards space station.

The price of developing or/and acquiring appropriate onboard medical imaging equipment must be weighed against the costs, in the absence of more timely and accurate diagnostic capability, of any of the following: (1) losing an astronaut who could have been saved, (2) suffering permanent disability (fully financially compensated by the government, of course) when a normal recovery might have been possible, or (3) initiating a \$100 million unscheduled shuttle launch for emergent recovery to earth when interim onboard management would have been medically acceptable. With closed head trauma, the probability of these errors is significantly higher because with most other injuries, the accuracy of differential diagnosis based on physical exam and "conventional" imaging is higher, or the deleterious consequences of a negative surgical exploration are lower, or both. These are compelling arguments for planning relatively sophisticated brain imaging capability at a relatively early interval in the course of space station development.

Similarly, the ability to diagnose and stabilize neck and spinal cord injuries can prevent major neurologic disaster; the inability to do so may result in either prolonged needless cumbersome immobilization, or what otherwise would be a preventable paralysis.

Along with good data, good management will require good management protocols. These will need to be developed by the neurosurgeons who constitute the neurosurgical component of the clinical specialty consulting network. In developing these protocols, it will be important to carefully define, in advance, what shall constitute "treatable" versus "untreatable" disorders and injuries, and what shall constitute criteria for onboard management versus initiation of immediate or delayed recovery to earth.

Also important to address will be the issue of propriety of preflight screening by imaging for specific abnormalities. In clinically neurologically normal persons, the probability of identifying a potentially clinically significant lesion is very

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low. Yet knowledge of the presence of an intracranial vascular malformation or extracranial carotid disease can now be obtained noninvasively, without risk, and at relatively low cost. It might well be judged cost effective to screen for such lesions, particularly for selected crew members and/or selected missions.

## **CHEST INJURIES**

Thoracic injuries are among the most immediately lethal in multiple injury patients. Terrestrially, about 25% of all trauma deaths result primarily from chest injuries, with most of these occurring before the victims reach a hospital. However, for those who reach the hospital, rapid evaluation and management can result in salvage from even severe and immediately life threatening thoracic trauma and prevent life threatening developments from lesser chest injuries. These are important reasons for mandating presence of capability to evaluate and manage chest trauma.

### **IMMEDIATE CONSIDERATIONS: THE "RAPID KILLERS"**

A limited number of conditions may evolve rapidly from blunt or penetrating thoracic trauma, beginning minutes to hours after initial injury, that may cause severe cardiopulmonary distress and rapidly lead to death, but that often can be successfully treated if quickly recognized. These are airway obstruction, open pneumothorax, tension (or severe) pneumothorax, massive hemothorax, flail chest with severe pulmonary contusion, and cardiac tamponade. The first 2 of these are readily appreciated on physical examination. The next 3 are usually detectable on physical exam, but diagnosis is greatly aided by plain film radiographs of the chest. The last must be suspected by physical exam after eliminating or treating other causes of hypotension, with central venous pressure measurement constituting a useful clue in some cases. The ability to monitor blood gases will be essential in assessing the initial severity and the response to management of many chest injuries.

Insuring adequacy of airway and ventilation are of primary importance in ill and injured persons. Therefore, the ability to suction the airway to clear secretions, to ventilate the lungs by application of face mask and positive pressure, to intubate the trachea by nasal or oral routes and ventilate with positive pressure, and to access the trachea directly via cricothyroidotomy and tracheostomy must be considered absolute essentials of emergency care in space.

The issue of ability to provide continuous medical suction in zero-G will be addressed in the description of the Fluid-Air Suction Technique with Separation of Liquid INdependent of Gravity (FAST SLING) unit in Part 2 of this report. Tracheal intubation will require ability to maintain relative positions of patient and rescuer. For the operating table setting, this is also addressed in description of the zero-G surgical module. At a site of injury, assuming a relative position which locks the rescuer's lower body to the victim's upper body (such as a neck straddle with legs wrapped around the chest, injuries permitting) may be the most expedient solution.

Initial, and usually definitive terrestrial treatment of pneumothoraces and hemothoraces is placement of a chest tube,

connected to a one-way (out) underwater seal, usually with application of about 20cm negative water pressure. For a severe tension pneumothorax it may be necessary to first relieve the tension with needle aspiration with or without attachment to a Heimlich (one-way) valve. For a truly massive hemothorax, immediate distress may be related as much to hypovolemia as to pulmonary dysfunction; therefore blood replacement may need to precede placement of a large chest tube. Since tube thoracostomy represents the mainstay of treatment of most significant chest injuries, it will be essential to be able to first perform tube thoracostomy, and then to provide a means of adjustable continuous suction, with ability to separate fluids from air in zero-G. These issues are addressed in the description of the zero-G surgical module, and the FAST SLING unit.

Flail chest with severe pulmonary contusion is treated by intubation and mechanical ventilator support, usually with positive end expiratory pressure (PEEP). PEEP can be applied with a mechanical outflow valve. The ability to intubate and mechanically ventilate will be crucial for a number of other conditions, as well.

Traumatic cardiac tamponade is much more likely in association with penetrating rather than blunt injuries. Initial relief may be provided by needle pericardiocentesis, unless the blood fails to defibrinate. Failure of cessation or of dramatic slowing of hemorrhage after placement of a chest tube, and failure to achieve or maintain decompression of cardiac tamponade with pericardiocentesis, are indications for open thoracotomy. While the chest is emergently opened, suture ligation of a lacerated intercostal artery or incision of a tense pericardial sac represent relatively minor tasks which, in the setting of appropriate indications, may be life saving. In addition, the equipment required beyond that needed for minor surgery is minimal. Therefore, capability to perform emergent thoracotomy should not be denied a surgeon on space station. However, the ability to replace blood loss needs to be addressed as a potential rate limiting step as regards overall ability to manage serious chest injuries, and particularly as regards propriety of emergent thoracotomy.

## **SECOND PASS CONSIDERATIONS: THE "LATENT KILLERS"**

In addition to the six potentially rapidly fatal problems in chest injury that were described as immediate considerations because severe cardiopulmonary distress is often present and the problems can be quickly diagnosed on physical examination, there are another halfdozen potentially lethal conditions that may be causing only modest cardiopulmonary difficulties initially, and that are usually not readily diagnosed on the basis of physical findings. These are rupture or laceration of the aorta, the diaphragm, the tracheobronchial tree, and the esophagus and contusion or infarction of the lung and of the heart. (The first of these has moved into the category of a "rapid killer" in those centers with trauma transport systems efficient enough to

transport to the hospital some of the 80% of the patients with transected aortas who usually die "at the scene" of the accident.)

The diagnosis of the first five of these is most likely to be made by proper interpretation of a chest roentgenogram. Hypoxemia detected by arterial blood gas determination, even when oxygen is being administered, may reflect (but is not specific for) pulmonary contusion. ECG changes may provide the only clue to a myocardial contusion or infarction. Indeed, electrocardiography, blood gas determinations, and roentgenography of the chest represent such crucial studies in the evaluation of chest injury that unless one of the so-called rapid killers mandates immediate intervention in a patient in extremis, these studies should be obtained as soon as possible after airway control and vascular access have been established and while physical examination is in progress.

A myriad of potential diagnoses awaits the careful examiner of a single anteroposterior roentgenogram of the chest, as indicated in the following table:

Thoracic Diagnoses by Chest Roentgenography	
FINDING	PROBABLE OR POTENTIAL PROBLEM OR ASSOCIATED DEFECT
Malpositioned tip of endotracheal tube	Airway obstruction, hypoventilation of left lung
Altered cardiac contour (unreliable)	Hemopericardium, preexisting cardiac disease
Widened mediastinum	Aortic injury
Pneumomediastinum	Bronchial or esophageal tear
Deviated mediastinum, hyperlucent hemithorax	Tension pneumothorax
Free peripheral pleural line	Small pneumothorax
Extrilar density, hyperlucent hemithorax	Large pneumothorax with lung collapse
Parenchymal lung densities	Pulmonary contusion, aspiration, lung collapse, ARDS
Fluid in pleural space	Hemothorax, hydrothorax, chylothorax, esophageal leak
Elevated diaphragm + viscera in chest	Ruptured diaphragm
Free air under diaphragm	Ruptured abdominal viscous
Lower rib fractures	Injury to spleen or liver
Middle rib fractures	Injury to lung, heart
Upper rib (and sternal) fractures	Tracheobronchial tear, great vessel injury
Subcutaneous emphysema	Injury to airway, lung, or esophagus
Malpositioned tip of CVP catheter	Erroneous monitor data, poor infusion, perforation of vessel
Malpositioned chest tube	Poor tube function, iatrogenic injury to mediastinum, diaphragm, or abdominal viscera

In addition to findings related to the "chest cavity," numerous other problems may be evident on the film, including fracture or dislocation of the clavicle and humerus; fracture of scapula, spine, or mandible; penetrating foreign bodies; and foreign bodies in the upper airway. The diagnosis of innumerable other significant disease processes has come to rely upon chest x-ray. Therefore chest roentgenography, to include, at minimum, the capability of a plain film, will be essential in management of chest trauma.

Contusions of the lung or heart are treated non operatively. The former may require mechanical ventilation with PEEP. Suspicion of laceration of the trachea or bronchus usually calls for investigation with a fibre optic bronchoscope, a light, compact instrument that may also have therapeutic application in removing mucus plugs resistant to external pulmonary therapy. Decision for evacuation versus onboard nonoperative management of these injuries will need to be carefully protocolled relative to the patient's overall condition.

Identification of a laceration of the aorta, diaphragm, or esophagus, or a large tear in the tracheobronchial tree is usually indication for early surgical intervention, even in the absence of immediate symptoms. Surgical intervention versus onboard non operative management versus early evacuation will need to be negotiated with the specialty consultants relative to the case at hand. A diaphragmatic rent without symptoms, or an airway leak evacuable with constant chest tube suction, might safely await recovery to earth for definitive repair. An esophageal tear, while best repaired immediately, might respond to chest tube drainage and antibiotic treatment while awaiting more definitive management after return to earth. An aortic laceration might remain hemodynamically stable for days to weeks, or might "blow-out" in minutes.

Since either definitive surgery or an emergent unscheduled shuttle recovery for several of these conditions is a major undertaking, and since diagnosis on physical exam and plain chest x-ray is uncertain, it is important to be able to confirm or disaffirm the presence or absence of the condition suspected before embarking on either path. For the aorta, digital subtraction angiography is the next most likely study. For other chest problems, plus the aorta, chest CT has become a standard of imaging. These 2 diagnostic radiographic modalities should be considered essential in the evaluation of chest illness and injury.

It should again be emphasized that the majority of significant chest injuries can be quite satisfactorily managed by control of ventilation and tube thoracostomy. Ability to replace blood loss also may be crucial, as previously mentioned.



## ABDOMINAL AND PELVIC INJURY

In terrestrial multiple-trauma patients, serious abdominal injuries are neither as frequent nor as lethal as serious chest and head injuries. Yet: (1) serious abdominal injuries tend to be less obvious and more difficult to diagnose than serious injuries to head, chest, and limbs; (2) more patients with serious abdominal injuries (almost 75%) are likely to have a concomitant major head, chest, or limb injury that may divert attention from the abdomen than vice versa; and (3) more patients with serious abdominal injuries (than patients with major head, chest, and limb trauma) who die subsequent to reaching a hospital (about 20%) do so because of delayed, inadequate, or inappropriate treatment rather than "uncorrectable" organ damage. Thus abdominal evaluation of a multiple-injury patient presents the surgeon with a challenge for accuracy and speed in diagnosis, the reward for which is a high probability of being able to intercept and surgically correct what are otherwise potentially fatal injuries.

The two major threats to life in abdominal trauma are hemorrhage and infection. Although hemorrhage remains the most immediate threat, intraabdominal sepsis has become a more common cause of death in those patients who survive the initial insult and are successfully resuscitated. The source of peritoneal cavity contamination is most commonly internal, from hollow viscus injury; less commonly external, a result of direct entry from a penetrating wound (poorly cared for surgical drain sites included); and even less commonly, hematogenous seeding of devitalized injured tissues. The presence of significant intraabdominal hemorrhage, a perforated or ruptured hollow viscus, or laceration or severe contusion of the pancreatobiliary tree structures are all absolute indications for early exploratory celiotomy. Surgical exploration per se is an almost certain means by which to identify or exclude such injuries. Yet so often with multiple injuries as with most critical illnesses and injuries, this is true: While the patient is almost certain to benefit from a therapeutic operation which accomplishes something, it is in the patient's best interest to avoid an operation that is only diagnostic. This truth will be even more applicable to space station injuries and illnesses. Prolonged observation or extensive studies to confirm severity of injury, and unnecessary celiotomy in an individual with serious and complicated associated injuries may be equally disastrous. Unnecessary unscheduled recovery to earth will be inconvenient and expensive. The crucial question in assessment of abdominal trauma, therefore, is how to rapidly and accurately determine whether or not there is injury to major vessels, gut, or solid viscera that requires early celiotomy for control and repair. A survey of the usual means of assessment--history, physical examination, laboratory data, and radiographic studies--unfortunately discloses that they are not always accurate.

## CRITIQUE OF DIAGNOSTIC CRITERIA FOR SURGICAL INTERVENTION

History too often is unreliable or unavailable, as with unconscious or intubated patients. Pain remains the most significant complaint, but its perception may be significantly modified by coexisting injuries and by the effect of drugs. Intense pain at fracture sites may divert attention from abdominal discomfort. Complaint of pain in a shoulder may not permit distinction of discomfort referred from irritation of the diaphragm by blood from that due to primary shoulder injury. Nausea and vomiting are common to many trauma patients and are nonspecific.

Physical examination, repeated at close intervals to detect changes, remains the cornerstone of diagnosis in abdominal trauma as in other abdominal states. Although careful physical examination may reveal a number of highly significant findings, many deserve some qualifying comments. Absence of obvious abdominal wall injury does not rule out the presence of extensive blunt intraabdominal trauma. There may be a 3 to 4 day delay before the appearance of extensive ecchymoses associated with retroperitoneal or deep abdominal wall injuries. The intrathoracoabdominal pathway of missiles cannot be reliably predicted from entrance and exit wounds because of a variety of possible positions of a patient at the time of injury and the possibility of internal skeletal deflections. In a crouching individual the diaphragm may reach the level of the fourth intercostal space; therefore any penetrating chest wound below the nipple line must be considered a potential thoracoabdominal injury. The presence or absence of bowel sounds is a poor criterion on which to base a decision in the immediate posttrauma setting, inasmuch as about 30% of patients with a significant intraabdominal injury will have active bowel sounds, while 30% of patients with a quiet abdomen will not have operative abdominal injuries. The presence of bowel sounds in the chest is very diagnostic of a diaphragmatic defect (acute or chronic), but their absence in that location does not rule out such injury. A bruit is present only in the minority of acute vascular injuries. The presence of a palpable pulse distally does not exclude the presence of major vessel injury proximally. Abdominal wall contusion or lower rib fractures may result in muscle spasm of the abdominal wall that prevents deep palpation and that can easily be confused with guarding related to chemical irritation of the peritoneum from blood or upper gastrointestinal contents. Reaction of different individuals to free blood or bile in the peritoneal cavity is quite variable, one person experiencing intense irritation from slight bleeding, while another may tolerate a large hemoperitoneum or bile leak without complaint. Leakage from the colon may exist without symptoms for hours, until a secondary inflammatory reaction is established. Alcohol and drugs in the system at the time of injury may markedly alter findings on abdominal examination.

Certain laboratory data can be quite helpful when abnormal, but otherwise are nondiagnostic. Except in chronic anemic states such as renal failure, a very low hematocrit value after injury must be interpreted as reflecting acute hemorrhage (particularly

if some time has passed since injury and intravenous crystalloid has been administered). However, a normal hematocrit value after injury does not exclude significant acute hemorrhage: Initially what leaves the vascular compartment and what remains within it have the same fraction of red cells. Only when what remains within the vascular compartment becomes diluted by translocation of interstitial fluid or by intravenous crystalloid infusion will the hematocrit value decrease. When a prolonged period of profound hypotension is associated with hemorrhage, a substantial fraction of what was formerly functional extracellular fluid may become unavailable for immediate attraction to the vascular space. Thus even with acute hemorrhage to the point of shock, several hours may pass before there is a significant fall in the hematocrit value. For most multiple-trauma patients, a significant decline in the hematocrit value is detected only after crystalloid fluid resuscitation.

Initial white blood cell counts in the range of 20,000 to 30,000 or more are associated with splenic injury, myocardial injury, and retroperitoneal bleeding, but counts in this range are so common in multiple-injury patients in general, particularly those experiencing blunt deceleration trauma, that early postinjury leukocytosis can usually be given no specific interpretation. It certainly cannot be interpreted as representing infection. A persistent increase in serum amylase is fairly diagnostic of significant pancreatoduodenal contusion or laceration or small-bowel perforation. However, even in the presence of significant pancreatoduodenal injury the amylase level becomes elevated less than half the time, and often the elevation is not observed for one or two days after injury. Thus in the absence of readily diagnosed pancreatoduodenal damage, serial serum amylase determinations are needed after abdominal trauma, and normal values in the first 24 hours do not exclude significant injury.

Early plain film roentgenographic examination of the abdomen is generally not helpful. Even high-quality anteroposterior supine plain films are notoriously unreliable in detecting small amounts of free air or even large quantities of free blood in the peritoneal cavity because of unfavorable distribution and poor density contrast with adjacent tissues. In a zero gravity environment, the usual positioning maneuvers which enhance probability of demonstrating free air will be ineffective. (Unfortunately, even in normal gravity state, the overall condition and associated injuries of the multiple-injury patient frequently do not safely allow such positioning.)

Therefore, because of (1) the lack of specificity and difficulty in interpretation of abdominal findings on initial physical examination, and laboratory and x-ray studies, (2) the potentially calamitous consequences of delayed recognition of and intervention for a significant vascular or visceral injury in the abdomen, and (3) the desire to minimize the number of unnecessary celiotomies performed, an algorithm is needed to determine whether the need is for early surgical intervention or for additional study and observation of the patient with a suspected

abdominal injury. The first decision in this algorithm is to categorize the abdominal injury as blunt or closed, versus penetrating or open; such classification is an immediate aid in assessment of potential organ injury.

### PENETRATING ABDOMINAL INJURIES

Penetrating abdominal injuries can be further categorized as high velocity or low velocity. It is generally agreed that all high-velocity missile injuries, and high-speed deceleration "impalement" injuries of the abdomen deserve urgent exploration. The benefit: risk ratio for routine exploration is favorable because of the high probability that a rigid object impacting the abdominal wall at high velocity will penetrate the peritoneal cavity, and that, having penetrated, it will retain sufficient energy to cause significant visceral or vascular injury or both.

Also of general agreement is urgent exploratory celiotomy for low-velocity penetrating abdominal wounds in patients who exhibit any of the following "mandatory" indications for surgical intervention: (1) evisceration, (2) signs of peritonitis (guarding, rebound tenderness, absence of bowel sounds), (3) free air, (4) evidence of intraabdominal hemorrhage (shock, gastrointestinal bleeding, hematuria, positive paracentesis or peritoneal lavage). These findings are present in only about 20% to 30% of all stab-wound patients received in terrestrial emergency departments.

What has not been so clear, in terrestrial experience, is how to assess low velocity penetrating injuries which present without mandatory signs for exploration. Several alternatives to the polar choices of routine exploration or observation while awaiting development of a clinical indication for surgery have been widely used and remain viable substitutes. In ascending order of probability of accurately identifying a surgically significant vascular or visceral injury these include: (1) an x-ray contrast sinographic study of the wound, (2) local exploration of the wound, (3) diagnostic peritoneal lavage, and (4) laparoscopy. Although valuable adjuncts, all of these procedures have their distinct drawbacks.

The first two, a sinogram and exploration of the wound under local anesthesia, are intended to determine if the peritoneum has been penetrated; a positive result constituting sufficient indication for celiotomy, and a negative result excluding intraabdominal injury. Both of these procedures suffer from three common defects: (1) a relatively high rate of false negative results (sinography more than exploration); (2) additional tissue irritation at the wound site that is confusing in a subsequent abdominal examination if operation is not immediately undertaken; and (3) the fact that proof of entry into the peritoneal cavity does not equal proof of surgically significant intraabdominal injury for most low velocity wounds. The false negative problem arises in part from the altered orientation of layers of the abdominal wall one to another at the

time of penetration compared to orientation at the time of injection of contrast medium or of dissection while the victim is on a litter. This Z-track effect tends to obliterate the probable straight-in path of the initial penetration.

Peritoneal lavage and laparoscopy offer greater opportunity to determine the presence or absence of significant vascular or visceral injury, as opposed to simply determining penetration or nonpenetration of the peritoneum by the other two procedures. The former determination is of distinct advantage in a multiple-injury patient because an unnecessary celiotomy may have a distinctly negative influence on management of coexisting extraabdominal injuries. Peritoneal lavage and local wound exploration are particularly attractive from the standpoint of being inexpensive and rapidly performed procedures that provide an immediate decision-making result without need to remove the patient from the site of resuscitation. This affords the surgeon maximum opportunity to simultaneously gain and maintain control of and evaluate associated injuries. Thus capability to perform both diagnostic peritoneal lavage and local wound exploration should be considered essential for space station.

#### **NONPENETRATING ABDOMINAL INJURY**

Nonpenetrating injury is the more common form of abdominal trauma associated with terrestrial multiple injuries in civilians. For purposes of assessment of potential intraabdominal injury, patients with nonpenetrating abdominal trauma may be conveniently divided into two groups: (1) those in whom abdominal examination reveals no abnormalities, and is judged to be reliable, and who have suffered neither unexplained blood loss nor hypotension; and (2) those in whom abdominal examination shows abnormalities, or is judged to be potentially invalid, or who have unexplained blood loss or hypotension, or both. In a patient who is alert and cooperative and who does not have confusing associated injuries, the presence or absence of abdominal pain and the findings on physical examination are highly accurate in identifying the presence or absence of significant blunt intraabdominal injury.

For patients in group 1, absence of abdominal complaints or findings in the presence of normal vital signs, normal hematocrit, and active bowel sounds virtually rules out significant hemoperitoneum or visceral perforation with spill of upper gastrointestinal contents, and physical examination therefore constitutes sufficient evaluation.

For patients in group 2, abdominal pain plus guarding and rebound tenderness are very suggestive of peritoneal irritation from blood or intestinal contents. Unfortunately these same symptoms and signs may be present (in the absence of hemoperitoneum or intestinal spill) due to associated injuries such as abdominal wall contusion or fractured ribs or pelvis, or may be absent (in the presence of hemoperitoneum or intestinal spill) due to variable patient response, associated neurologic injury, or

altered state of consciousness, any of which may make abdominal examination unreliable. When hypotension, unexplained blood loss, or both are present, the inability to quickly and accurately distinguish the presence or absence of hemorrhagic injury within the abdomen on the basis of physical examination becomes even more distressing. Unlike other locations that may contain major hemorrhage that is easily discernible by physical examination and roentgenography (thorax, long-bone fracture sites), or in which spontaneous tamponade is likely (fracture sites, retroperitoneum), the peritoneal cavity is able to sequester a significant volume of blood that is not readily evident and where tamponade does not readily occur. Thus in a multiple-injury patient, basing the decision whether to explore or not to explore the abdomen only on the physical examination (and plain-film x-ray study) had led to both too many unnecessary celiotomies, and too many late surgical interventions for serious intraabdominal injuries. It is for all these reasons that diagnostic peritoneal lavage has become the mainstay in the evaluation of blunt abdominal trauma for patients in group 2.

Peritoneal lavage has assumed this key role in diagnosis of blunt abdominal trauma because it is a procedure that has demonstrated itself to be (1) extremely accurate in identifying the presence or absence of significant intraperitoneal hemorrhage (false positive and negative rates less than 2%); (2) very safe (associated morbidity less than 5%); (3) inexpensive and easy to perform to produce a decision-making result early in the course of overall evaluation without need to remove the patient from immediate supervision of the trauma surgeon. The guidance provided by peritoneal lavage, both in avoiding unnecessary celiotomy and in earlier identification of hemoperitoneum and intestinal leakage as indications for celiotomy, has proven so important in terrestrial evaluation and management of multiple-injury patients, and the procedure so simple, that, as previously noted, this capability should be considered essential for space station.

The majority of terrestrial multiple-injury patients with blunt abdominal trauma fall into group 2. The following table lists indications for and relative contraindications and alternatives to use of peritoneal dialysis in evaluation of group 2 patients.

Indications and Contraindications for Diagnostic Peritoneal Lavage
INDICATIONS IN GROUP 2 BLUNT ABDOMINAL TRAUMA PATIENTS
Abdominal pain, positive abdominal examination, or both
Hypotension, unexplained blood loss, or both
Neurologic injury, or altered state of consciousness, or both, rendering patient unable to complain or rendering abdominal examination unreliable
Associated injuries (extensive abdominal wall contusion, gross hematuria, fractured lower ribs, spine, pelvis) that make intra-abdominal injury suspect and that may confuse abdominal examination
Extra-abdominal injuries requiring an interval under anesthesia for early repair
CONTRAINDICATIONS
Decision to operate anyway (penetrating injury, rapid expanding abdomen and hypotension)
Gravid uterus near term
Inability to empty the urinary bladder (unkindly)
RELATIVE CONTRAINDICATIONS (A SELLINGER TECHNIQUE ENTRY CAN BE MADE AT A SITE AWAY FROM SCAR OR HEMATOMA)
Previous lower abdominal surgery
Abdominal wall hematoma
ALTERNATIVES
Bilateral needle paracentesis*
Repeated abdominal examination and monitoring of vital signs
Exploratory celiotomy
*Caution: up to 40% false negative rates reported

ORIGINAL PAGE 22  
OF POOR QUALITY

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OF POOR QUALITY

Although accuracy of identifying laceration of a hollow viscus or the pancreas on the basis of laboratory quantitation of white blood cell and amylase content of lavage fluid does not approach that for identifying significant hemorrhagic injury on the basis of red cell content, visceral injury is certainly suspect if these values are markedly elevated. Normal white blood cell and amylase values in lavage fluid by no means exclude such injury, particularly to retroperitoneal portions of duodenum, pancreas, or colon. However, the majority of patients with significant retroperitoneal injuries have associated peritoneal cavity injuries and, hence, heme-positive peritoneal lavage.

### RADIOGRAPHIC STUDIES

Although the largest fraction of the abdominal injury decision making process is based upon history of mechanism of injury, physical exam, stability of vital signs, and peritoneal lavage, radiographic studies have a role.

**Plain films:** A chest roentgenogram is considered an integral part of abdominal evaluation because of the frequent association of thoracic injuries with abdominal trauma and the numerous diagnoses that may be extracted from this single film which were tabulated in the discussion of chest injuries. Although generally less "directly" than diagnoses gleaned from chest x-ray, a number of injuries may be suspected from careful examination of abdominal plain films, as indicated in the following table:

Diagnoses from Plain Films of the Abdomen	
FINDING	PROBABLE OR POTENTIAL INJURY
Free air	Laceration or perforation of hollow viscus
Extraluminal gas (stippled or bubble appearance) in mid upper abdomen	Retroperitoneal rupture of duodenum
Extraluminal gas in left lower quadrant	Rupture of cecocolic colon
Lower rib fractures	Injury to spleen or liver
Large water density mass effect in lateral upper quadrant	Injury to spleen or liver
Medial displacement of stomach with indentations along greater curvature	Splenic injury with hemorrhage into gastrosplenic ligament
Bowel gas pattern in chest	Ruptured diaphragm
Loss of psoas shadow	Retroperitoneal hemorrhage
Enlarged renal mass shadow	Renal hemorrhage
Fracture of transverse lumbar spinous processes (particularly T11, T12)	Renal injury, pancreatic injury, retroperitoneal hematoma
Pelvic fracture	Bladder injury
Bladder (or Foley catheter balloon) displaced upward or laterally	Pelvic hematoma, ruptured bladder
General "ground glass" haziness, small bowel gas pattern floated to center of abdomen, separation of left or right colon gas pattern from flank fat line	Hemoperitoneum (late signs, with large quantity of free blood)
Bullet or shrapnel fragment	Location aids in defining intra-abdominal trajectory
Nasogastric tube not in stomach	Poor tube function
Chest tube in abdomen	Iatrogenic perforation of diaphragm (+ viscera)

Radiographic plain-film (indirect) evidence of retroperitoneal or pelvic hematoma may be very helpful in accounting for lost blood when the findings on peritoneal lavage and the chest roentgenogram are normal. Enough hemorrhage may occur in and remain confined to the retroperitoneal space (as much as 2 liters in an adult) to produce profound hypotension without any overt localizing sign until appearance of flank ecchymosis several days later. These considerations are additional arguments for plain film x-ray capability on space station.

**Angiography:** Except in aortic and renal injuries (discussed in the next section), angiography is usually not considered among the crucial studies in the initial evaluation of abdominal trauma. Preoperative angiograms are most helpful in connection with (1) decision for reoperation in a complicated injury to liver, pancreas, or root of mesentery; (2) reevaluation (and occasionally therapeutic clot injection) of persistent bleeding from around pelvic fractures; (3) reevaluation of the condition of a high-risk patient for whom unnecessary celiotomy is highly undesirable and for whom the decision for or against surgery still cannot safely be made on the basis of physical examination, vital signs, and diagnostic peritoneal lavage. For other reasons to be discussed, digital angiography capability is important for space station.

**CT scan:** In recent years, CT scanning has emerged as the radiographic modality most likely to displace peritoneal lavage as the most definitive indication of intraabdominal injury requiring surgical intervention. For several other reasons to be discussed, CT scanning capability is second only to plain film x-rays as regards radiographic imaging capabilities essential for space station.

**Radionuclide scans:** For a high-risk patient with equivocal findings on physical examination and peritoneal lavage, and for a patient who is recovered in a stable status many hours after injury, the ability to identify or exclude significant abdominal visceral injury without celiotomy remains a worthy goal. In these situations, scintigraphy appears to have at least equaled, if not surpassed, angiography for evaluation of liver and spleen injuries. Scintigraphy capability for abdominal diagnoses, however, remains of low priority compared to other modalities discussed.

#### **DECISION FOR IMMEDIATE CELIOTOMY VERSUS EARLY RECOVERY TO EARTH**

For the abdominal-trauma patient, received in a terrestrial rural community hospital, in whom indication for celiotomy is identified, the question whether to perform the operation at the local facility or to transfer the patient to a major medical center will sometimes arise. The answer will depend on the stability of the patient's condition and nature of associated injuries, anticipated delay in effecting a transfer, care available during transport, expertise of surgeons available in



the community hospital, and ability of the local facility to support a major surgical effort. Similar considerations will necessarily influence the decisions as regards an abdominal trauma patient on space station. Fortunately with most potentially life-and limb-threatening injuries (cerebral, thoracic, peripheral vascular, skeletal) the level of specialty expertise needed to successfully repair the probable lesion can be fairly well estimated preoperatively. The issue is less clean-cut with abdominal trauma, in which the precise nature of the injury is usually unknown before celiotomy. Increased preoperative use of CT scanning may change that fact, however.

Hemorrhagic injury, the most immediate threat to life in abdominal trauma, is also the most immediately evident. If hypotension persists in a trauma patient in whom hemoperitoneum was identified by peritoneal lavage, a surgeon who does limited abdominal surgery in a remote setting may serve that patient well by removing or repairing a ruptured spleen. Indeed, a lengthy transfer in this circumstance is likely to be of greater risk than surgery. But if upon opening of the abdomen a major liver laceration, pancreatoduodenal injury, or renovascular-caval disruption is encountered, the outcome may be less satisfactory. Even the experienced trauma surgeon would find hepatic lobectomy or renovascular repair a formidable problem in a rural community hospital without assistants and without liberal blood bank support. The impact of these limitations is likely to be magnified during early years on space station.

Injury to hollow viscus, less immediately threatening to life, is also less immediately evident. Nevertheless, when overlooked or mismanaged operatively, the resultant intestinal leak can kill just as surely, although more slowly, than hemorrhagic injury. Decisions regarding repair versus resection of a perforated gut, primary anastomosis versus temporary ostomy, and repair and drainage of complicated rectoperineal injuries challenge the trauma surgeon to provide the correct solution during the first operative intervention since failure to do so may preclude opportunity for successful revision several days later.

Less dramatic, nontraumatic abdominal surgical problems, such as appendicitis, may represent less immediate pressures as regards decisions for operative intervention versus transfer. However that is not cause to automatically assume a nonoperative, recover-to-earth posture. Just as the threat to life is less immediate, so is there greater ability to effect a definitive surgical cure with a relatively straight forward surgical procedure onboard, without need for complicated equipment or extensive laboratory and blood bank support. Many such patients should be expected to be eating, "ambulating," and back to duty within a few days.

Therefore, when celiotomy appears to be indicated in an abdominal injury or abdominal illness patient onboard space station, availability of a mechanism of recovery to earth, acceptable to the responsible physician, will also have to be assessed. If

recovery is not available or acceptable, it will be necessary to proceed with surgery. The capability to do so is essential in space station planning. If recovery to earth by an acceptable means and in an appropriate time frame is available, then the surgeon onboard will need to confer with the appropriate specialty consultants in order to select the optimum location for the operation according to the specific circumstances surrounding the individual case. When emergent surgery for abdominal trauma is undertaken onboard as a life-saving measure, and complicated viscerovascular injuries are encountered whose definitive repair is beyond the capability of the facilities and assistance available to the onboard surgeon, straightforward methods should be employed to gain control of continuing hemorrhage (packing, ligatures as appropriate) and irrevocable procedures avoided. Early recovery to earth for reoperation should then be arranged, if possible. Thus, short of planning for definitive management of all possibilities, the capability to perform routine celiotomy onboard, before early recovery to earth, may be life saving. A high degree of accuracy of preop diagnoses clearly will be critical in the decision making process, just as it will in avoiding the unnecessary celiotomy.

## GENITOURINARY TRACT INJURIES AND EMERGENCIES

Injuries to the urogenital system can be conveniently classified in several ways: Anatomically it is useful to localize the site of injury to kidney (parenchyma, collecting system, pedicle); ureter (upper, middle, lower), bladder (intraperitoneal, extraperitoneal); urethra (posterior, anterior); or external (male) genitalia. Etiologically it is helpful to categorize the injury as penetrating or nonpenetrating. Clinically it is meaningful to identify renal injuries as minor, major, and critical.

The kidney is frequently injured, being second only to the spleen as the viscus most commonly injured by blunt abdominal trauma, terrestrially. Contusion of the renal parenchyma without rupture of the capsule or tear into the collecting system is a minor injury to the kidney. Hematuria may or may not be gross initially but usually rapidly abates. Any signs and symptoms related to the contusion should steadily improve; observation only is indicated. Over 80% of all renal injuries fall into this group. Major injury to the kidney consists of parenchymal laceration with extension through the capsule and into the collecting system but without disruption of the renal pedicle. Shock and hematuria may or may not be present initially, but signs and symptoms are likely to intensify rather than abate with time. Less than 15% of all renal injuries fall into this group. Fragmentation of the kidney or extension of a laceration into the vascular pedicle is a critical injury. Blood loss is likely to be severe within a short interval. Less than 5% of renal injuries fall into this group.

Most ureteral injuries are a result of penetrating trauma.

Lacerations of the bladder from penetrating injuries vary in location according to the pathways of the missile. Ruptures of the bladder from blunt trauma are almost equally distributed between extraperitoneal (usually associated with pelvic fracture) and intraperitoneal locations (usually associated with disruption of a full bladder at its weakest point, the dome), with less than 10% being combined intraperitoneal and extraperitoneal injuries.

Injuries to the urethra are usually classified according to their location in relation to the urogenital diaphragm: Those below (anterior) are more frequent, while those above (posterior) pose more difficult management problems. Injuries confined to the membranous urethra, which traverses the urogenital diaphragm, are extremely rare. Posterior injuries result from blunt trauma that causes the prostate to be sheared from its connection to the urogenital diaphragm and puboprostatic ligaments and the urethra to be disrupted. Posterior urethral tears are about equally divided between complete and incomplete. Even when the urethra is severed the sphincteric activity of the bladder outlet remains intact. Thus the bladder is likely to remain full and there may be only minimal or no extravasation of urine.

## CRITIQUE OF DIAGNOSTIC CRITERIA

Initial evaluation of injury to the urogenital system is conveniently integrated with that of the abdomen and pelvis. In an alert cooperative patient, certain aspects of history may lead to a suspicion of urinary tract injury. Deep flank pain and bloody urine suggest renal damage. Suprapubic pain, inability to void, or passage of blood per urethra suggests bladder or urethral injury or both. However, in a patient with multiple injuries, history is frequently unavailable, unreliable, or nonspecific. Although inability to void is more specific than many complaints, most multiple-injury patients will not have attempted to void when initially seen. Pain from associated injuries and the general confusion of the resuscitation scene may inhibit even an alert patient from attempting to void even in the absence of specific lower-tract injury.

Except for external genitalia trauma, physical examination is also unreliable and nonspecific in detecting urinary tract injury. Deep flank pain (or mass) may or may not be present with renal injury and if present may be due to associated extrarenal trauma. Deep flank ecchymosis may require several days to become superficially evident after a major perirenal hemorrhage. Suprapubic tenderness may or may not be present with bladder injury, and if present may be due to abdominal wall contusion or pubic fracture without bladder injury. Generalized abdominal tenderness may or may not be present with intraperitoneal bladder rupture and extravasation of urine, and if present may be due to abdominal wall contusion or injury to other intraabdominal organs. A rectal mass may or may not be present with perivesical hemorrhage, and if present may be related to pelvic fracture without bladder damage. Superior displacement of or inability to palpate the prostate (and inability to void) strongly suggests disruption of the urethra above the urogenital diaphragm, but normal position of the prostate (and ability to void) does not exclude incomplete laceration of the urethra. A drop of blood at the urethral meatus and perineal or penile hematoma may or may not be present with laceration of the anterior urethra.

### IMMEDIATE CONSIDERATIONS: URINALYSIS, BLADDER CATHETERIZATION

With these limitations of history and physical examination to identify significant urologic injuries, an algorithm is needed for evaluation of the urinary tract, particularly in a multiple-trauma patient. Of 2 key principles in the algorithm, the first is that every patient with any of the foregoing symptoms or findings, and every multiple-trauma patient, deserves a urinalysis early in the course of evaluation, with particular attention being given to presence or absence of hematuria. Thus the capability to perform urinalysis must be considered essential in space station planning, not only for evaluation of urologic trauma, but for evaluation of several other potential urologic and many other potential internal medicine problems.

The alert, cooperative patient without limitation of motion imposed by associated injuries should be asked to void spontaneously into an appropriate collection container: Blood in a spontaneously voided specimen cannot be due to iatrogenic urethral trauma in an attempt to pass a catheter. For the patient who is unconscious, uncooperative, or unable to void, the menstruating female, or a female with associated injuries that prevent application of an appropriate urine collection device, it will be necessary to attempt to pass a urethral catheter to obtain the initial urinalysis specimen. An indwelling bladder catheter should be placed to continuously monitor urine output in any patient who is or was initially in shock. Preparation to pass a transurethral bladder catheter must also be considered an essential component of space station planning.

The issue of when, post trauma, a Foley bladder catheter should be passed is without uniform agreement. Ideally, to prevent the possibility of converting an incomplete urethral laceration to a complete disruption, it would be well to exclude the presence of urethral laceration before inserting a urethral catheter. (Transection of the posterior urethra is difficult to repair by any means, with a high incidence of stricture, incontinence and impotence.) Identification or exclusion of this injury requires retrograde urethrogaphy (10-30 ml of full-strength contrast material used for intravenous injection is introduced into the urethral meatus by means of a catheter-tipped syringe.) To prevent the possibility of obscuring visualization of a lower ureteral injury by extravasation of contrast material from a bladder laceration, it is well to perform excretory pyelography before retrograde cystourethrography. This sequence usually introduces significant delay before obtaining the initial urinalysis and establishing a track on urine output. For a patient with isolated pelvic injury, particularly with inability to void, a bloody discharge from the urethra, or both, if the condition remains stable this is an acceptable, even preferred, sequence. However, this optimum sequence for ruling out the rare (but important) urologic injury that urethral laceration represents is neither realistic nor altogether safe from the standpoint of overall evaluation and management of the majority of multiple-injury patients, particularly those who are hypotensive. Therefore, for trauma patients with the aforementioned indications for bladder catheterization (except in a stable, isolated pelvic injury), it is an acceptable compromise to make one gentle attempt, under sterile conditions, to pass a Foley catheter.

Failure to pass the catheter implies need for further study before any more attempts are made. Pelvic fracture is associated with almost every posterior urethral laceration from blunt trauma. If pelvic fracture is clinically evident or suspected and a catheter will not pass immediately, a urethrogram is definitely needed. If there is not a penetrating injury and pelvic fracture is neither clinically evident nor seen on a plain film of the pelvis, there is little probability of urethral disruption.

Fortunately in the majority of trauma patients with indication for bladder catheterization, it is possible to insert a Foley catheter with ease on the first attempt. Success allows early determination of presence or absence of hematuria and early monitoring of urine output. Except in the presence of gross hematuria, a urine specimen should be centrifuged, and a portion of resuspended sediment examined microscopically. These microscopic urinalysis capabilities are important for evaluation of other diseases as well as trauma.

It should be noted that degree of hematuria does not correlate well with magnitude of urinary tract injury: Minor renal contusion may result in grossly red urine, while major pedicle damage with obstruction to renal artery flow may be accomplished by little or no hematuria. Gross hematuria out of proportion to the trauma apparently sustained has often been discovered to be due to preexisting renal disease (neoplasm, glomerulonephritis, hydronephrosis, congenital malformation). Distinct hematuria may result from traumatic insertion of a catheter. Urinalysis is normal in about one-third of patients with isolated ureteral injury. These qualifying observations notwithstanding, more than 90% of kidney and bladder injuries will result in hematuria, and gross hematuria clearly represents significant hemorrhagic injury to the urinary tract.

Exsanguinating hemorrhage may occur from an injury severe enough to fragment a kidney or disrupt the renal vascular pedicle. When associated with shock unresponsive to rapid infusion of 2 liters of crystalloid, such injury is indication for infusion of whole blood and rapid removal to the operating room for emergent celiotomy and control of the renal pedicle followed by ligation or repair. Profound shock, gross hematuria, and an expanding flank mass suggest critical renal injury, but in most cases the presenting features will not be specific. The situation is more likely to be that of apparent intraabdominal injury, specific organs unknown. Decision for immediate surgery versus radiographic evaluation must be based on the patient's condition and response to resuscitation efforts, as described in the section on abdominal injuries.

#### **RADIOGRAPHIC STUDIES: IVP**

The remainder of the initial evaluation of urinary tract injury is radiographic. The second key principle in the algorithm is that the finding of gross or microscopic hematuria is sufficient indication for intravenous pyelography (IVP). In a multiple-injury patient, hematuria should be considered an absolute indication for this study. A history of an allergic reaction to previous intravenous iodinated contrast studies is a relative contraindication to intravenous pyelography. CT scanning and ultrasonography may be useful alternative diagnostic modalities.

In addition to presence of a parenterally administered contrast agent, performance of an IVP requires only plain film x-ray

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capability. The importance of this capability for other purposes has already been stressed. As with other anatomic areas and potential injuries of interest, an IVP may yield a number of potential diagnoses, as indicated in the following table:

Urinary Tract Diagnoses by Intravenous Pyelography	
FINDING	PROBABLE OR POTENTIAL PROBLEM
Fracture of transverse processes of T1, T2	Renal injury, possibly severe enough to involve vascular pedicle
Bilateral nonvisualization of kidneys	Low flow state (hypovolemia, hypotension) vs bilateral injury, or preexisting disease
Small kidneys or marked disparity in size	Preexisting renal disease
Bilateral delayed or poor visualization	Low flow state vs bilateral contusion or renal artery spasm
Unilateral nonvisualization	Renal contusion, renal artery spasm, renal artery occlusion by intimal tear flap, congenital (or surgical) absence
Nonvisualization or poor visualization of a segment and its calyx	Renal laceration or rupture
Extravasation of contrast from a kidney	Renal parenchymal laceration extending into collecting system
Isolated hydronephrotic ureter	Distal ureteral injury with obstruction, obstruction of ureter by hematoma
Extravasation of contrast from ureter	Ureteral laceration
Fracture of pelvis	Bladder injury
Distorted shape (tear drop, crescentic) or displacement (upward, lateral) of bladder or both	Perivesical hematoma, bladder injury
Extravasation of contrast agent from bladder * into peritoneal cavity into retroperitoneum	Bladder rupture or laceration at dome at extraperitoneal site

\* May need postdrainage film to detect

Although not all of the potential findings are specific, many of them represent indications for additional x-ray studies or surgical intervention. An accounting of these indications follows.

### Kidney

Bilateral poor visualization or nonvisualization (most often due to low flow state) is an indication for CT scanning or ultrasonography in order to more precisely define the cause. Both these modalities are very useful in urologic evaluation; their comparative advantages and disadvantages will be discussed in the section on radiographic imaging.

Unilateral nonvisualization or other strong suspicion of renal vascular pedicle damage is indication for renal angiography. Digital angiography, particularly with anticipated increases in resolution with future generation equipment, will probably be the preferred modality for space station.

Early identification of renal artery thrombosis or other vascular pedicle injury is usually sufficient indication for early operative intervention; because, by repair of a defect as simple as an intimal flap tear, a kidney may be salvaged that would otherwise be lost to ischemic necrosis. However, under many circumstances probable during early space station activities, the immediate risk of attempting such repair would probably be judged by the surgeon onboard and remote specialty consultants to exceed the long term risk of accepting the loss of one kidney. The delay involved in a recovery to earth, even from LEO, would push the time limit within which ability to salvage an ischemic kidney

is likely. These sorts of evaluations of relative risks and influences of delays will be important contributions of consultants who are both expert in their clinical specialty areas and highly familiar with the operational environment in space.

When major renal injury is identified or strongly suspected from the IVP, as is the case particularly with extravasation of contrast, renal arteriography or CT scanning is extremely useful to more precisely assess the extent of both damage and hemorrhage, which in turn guides the decision concerning operative intervention and whether to attempt repair or to remove the kidney.

Penetrating renal injuries and those with evidence of continuing brisk hemorrhage usually deserve early exploration by way of an anterior transperitoneal approach.

Despite extravasation, major renal injury resulting from blunt trauma that is not complicated by continuing hemorrhage or evidence of infection is usually best managed expectantly. This will be particularly true for space station. For such injuries, surgical intervention in the early posttrauma period too often results in nephrectomy for otherwise viable kidneys; bleeding that had been checked by compression resumes when Gerota's fascia is opened, making it difficult to precisely assess damage. Conservative management should be pursued with urologic specialty consultation.

#### **Ureters**

Ureteral injury may be diagnosed by IVP x-ray or ultrasound exam. Evidence of ureteral injury (extravasation, hydronephrosis) is indication to obtain early urologic consultation. Ureteral injuries require operative repair; however, such injuries are not usually life threatening. Therefore, in the space station setting, initial treatment could consist of nonoperative observation, or limited drainage of urine collection.

#### **Bladder**

Extravasation of contrast medium from the bladder is evidence of laceration or rupture. Except perhaps for small extraperitoneal perforations, bladder defects should usually be surgically closed by way of a suprapubic or intraabdominal approach as appropriate, using three layers of running absorbable suture and establishing postclosure drainage via suprapubic cystostomy (a Foley urethral catheter may suffice in female in the absence of associated urethral or pelvic injury). In the space station setting, catheter drainage alone might suffice as initial therapy. It should be noted that extraperitoneal rupture of the bladder is almost always associated with a pelvic fracture.

#### **Urethra**

For a patient in whom there is strong suspicion of urethral



laceration (pelvic fracture, inability to void, bloody urethral discharge, displacement of the prostate) or a patient in whom an attempt to pass a Foley catheter has failed, a retrograde urethrogram is indicated. Plain x-ray capability is needed to accomplish this study. Demonstration of a partial or complete urethral disruption (or continued inability to pass a Foley catheter after inability to demonstrate a laceration) is indication for early urologic consultation. If the patient can void, it will probably be best, in the space station setting, to avoid further immediate manipulation. If a Foley catheter has been passed and the bladder is adequately drained, that should constitute adequate initial therapy. Otherwise, suprapubic drainage of the bladder must be established. There is obviously some urgency in accomplishing this for a patient who can neither void nor have a Foley catheter inserted. The most definitive and certain technique is placement via surgical incision. However, when instability of the patient's condition or priority of management of associated injuries precludes early removal to an operating room setting, percutaneous placement of a suprapubic bladder drainage catheter may be necessary.

When percutaneous suprapubic bladder catheterization is contemplated after trauma, it should be remembered that the same pelvic injury and associated hematoma that may be preventing catheter insertion per urethra may distort and displace the bladder so as to complicate a percutaneous approach from above. In this setting, complications of suprapubic bladder catheterization can be minimized by use of the Seldinger technique instead of a trocar or a deep cutdown: An 18-gauge needle is the sharpest object which must locate the bladder through a hematoma; certainty of approach to the lumen of the vesicle is assured before advancing the larger plastic catheter.

#### **NON TRAUMATIC UROLOGIC EMERGENCIES**

The urologic emergencies most likely to be encountered on space station are of a nontraumatic nature. Nevertheless they may be just as, or more, incapacitating and urgent in nature. Torsion of the testis, ureteral colic, acute urinary retention, and urinary tract infection are among the more important of these.

There is no reliable way to pre screen for susceptibility to torsion. The diagnosis is based upon a very characteristic history, and findings on physical exam. Treatment is early operative intervention involving a relatively minor and superficial surgical procedure for which space station should have capability.

Formation and passage into the ureter of a renal stone is an event for which there is a higher than usual probability of occurrence during space flight and space station activities. This increased risk relates to proclivity to hypercalcuria, dehydration, and increased concentration of urine. Probability of occurrence must be considered further increased in anyone who has a prior terrestrial history of renal-ureteral lithiasis.

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Ureteral colic is often an extremely incapacitating event, at least at intervals. Such intervals may recur over hours to several days before a stone finally passes. In the past, these facts have prompted the judgment that prior history of ureteral lithiasis is sufficient criteria for disqualification from space flight.

Diagnosis of ureteral stone is strongly suggested by history and physical exam, strengthened by presence - but not weakened by absence - of blood on urinalysis, and further corroborated by IVP x-ray or ultrasound. Treatment is usually nonoperative, with administration of narcotic pain medication, and large volumes of fluids to stimulate increased urine flow. Operative intervention is usually late, if used at all, because most stones will pass within a few hours, most of the rest within a few days, and almost all within a week. Urologic consultation will be appropriate to monitor progress and negotiate management decisions as regards early recovery to earth versus waiting out resolution onboard. Several new drugs have appeared on the market recently which appear effective in inhibiting formation of particular kinds of kidney stones.

Urinary retention is easily diagnosed by history and physical exam, can sometimes be relieved by pharmacologic stimulation, and is usually easily treated by transurethral catheterization. Failure to catheterize from below suggests need for suprapubic drainage, as previously described. History of previous retention terrestrially would probably represent a relative contraindication to space flight. Elective preflight catheterization might represent a good screening procedure, both from the standpoint of discovering a potential urethral or bladder outlet stricture, and from the standpoint of verifying the ability to pass a catheter if necessary emergently.

Urinary tract infections to be considered, in addition to cystitis, include pyelonephritis, prostatitis, and epididymitis. Diagnosis is supported by microscopic urinalysis capability. Treatment is antibiotics; antibiotics can be chosen fairly effectively without culture.

In considering both prevention and treatment of anticipated problems, the urinary tract is an anatomic structure which may benefit to a greater extent than many other organ systems from preflight confirmation of normalcy or demonstration of a specific variant by CT scan, IVP, etc., as discussed in the section on radiographic imaging.

## **LIMB INJURY**

It has been pointed out that in remote populations of relatively young persons, recreational activities have accounted for a significant fraction of medical problems. Of injuries associated with recreational activities, limb injuries are among the most frequent.

A common pitfall in approaching a multiple-injury patient is to allow a striking deformity of a limb associated with a skeletal injury to attract immediate attention, with resultant diversion of that attention from other less obvious, but more serious, injuries. Yet early recognition, reduction, and splinting of fractures and dislocations can relieve pressure on and prevent further damage to major vessels, nerves, and joints; often providing the margin of protection necessary to make the difference between permanent disability and recovery of function. Thus although it is an important adage in the management of multiple trauma that (particularly skeletal) injury of the limbs is seldom the most urgent problem, it is also important to recognize that: (1) limb injuries are frequently associated with multiple trauma; (2) the presentation of some of the more serious limb injuries may be rather subtle; and (3) the early evaluation and management of a limb injury often determines the survival and function of the limb.

It is useful to consider limb injury in terms of 5 components: skin, underlying soft tissue (muscle and tendon), nerves, vessels, and bone. However, in the multiple-trauma patient it is important to note that injuries to these systems seldom are isolated phenomena. Coexistence of damage to arteries, veins, and nerves, and destruction and contamination of adjacent muscle and soft tissue, in addition to fractures and dislocations, are factors that bear heavily on overall management and outcome of limb injury.

It is also useful to categorize limb injuries according to mechanism of injury: those which are a result of penetrating trauma versus those which are a result of blunt trauma. Knowledge of mechanism of limb injury immediately provides a great deal of insight into which components may be injured, in what manner, and to what extent.

### **DIAGNOSTIC CRITERIA**

Diagnosis of specific injuries will be dependent upon physical examination and appropriate imaging. Criteria for diagnosis by physical exam include the following:

**Fracture injury** in a limb should be suspected whenever one or more of the following are present:

1. Obvious deformity
2. Persistent and localized pain
3. Swelling, effusion, ecchymosis, hematoma or crepitation.

4. Neurovascular compromise distal to any of these findings
5. Inability or unwillingness to use the part, or marked limitation of motion.

**Dislocation** should also be suspected when any of the above findings are localized to a joint. Findings characteristic of the more common dislocations are as follows:

1. Acromioclavicular: prominence of the outer third of the clavicle
2. Shoulder: lateral subacromial depression or hollow, compromise of axillary artery
3. Elbow: posterior prominence at the elbow, compromise of brachial artery
4. Hip, posterior: internal rotation of the thigh, sciatic nerve compromise, associated patellar fracture
5. Hip, anterior: external rotation of the thigh, femoral artery and nerve compromise
6. Knee, anterior: anterior prominence of the proximal tibia, compromise of popliteal artery and peroneal nerve
7. Patella: lateral prominence of the patella
8. Ankle, medial: prominence of lateral malleolus
9. Ankle, lateral: prominence of medial malleolus, compromise of posterior tibial artery

**Ligament injury** should be suspected whenever there is a fracture or dislocation, or when there is joint instability. Ecchymosis and swelling are very characteristic.

**Tendon injury** should be suspected whenever there is inability to selectively flex, extend, abduct, or adduct a part distal to a laceration over the course of the corresponding tendon.

**Peripheral nerve injury** should be suspected whenever one or more of the following are present:

1. Paralysis
2. Paresthesia
3. Asymmetry of strength
4. Selective loss of motor function with preservation of sensation
5. Loss of light touch sensation with preservation of pain
6. Prolonged dislocation of the elbow, hip, knee, or ankle

**Brachial plexus injury** should be suspected when there is: (1) loss of function of all 5 major nerve distributions in the upper limb (complete injury), (2) selective loss of function of the shoulder and elbow with motion and sensation of the hand remaining intact (segmented upper lesion), or (3) loss of function of all 3 nerves in the forearm and hand with preservation of function at the shoulder and elbow (segmental lower lesion.)

**Arterial injury** should be suspected whenever one or more of

the following are present:

1. Brisk external bleeding, particularly if bright red and pulsatile
2. A rapidly expanding hematoma
3. A penetrating wound near the course of a major vessel
4. Severe soft tissue damage (crush, avulsion, blast) near the course of a major vessel
5. A long bone fracture or prolonged joint dislocation, particularly if associated with one or more of the signs or symptoms described in (6) below
6. One or more of the 6 "p's" classically associated with an acutely ischemic limb: pulselessness, pallor, poikilothermia, pain, paresthesia, paralysis
7. A systolic bruit or thrill over a pulsating hematoma, or a continuous bruit over a penetrating wound
8. Absence of distal flow by Doppler ultrasound study in the presence of one or more of the above findings

**Compartment syndrome** should be suspected when any of the signs of neurovascular compromise (the 6 "p's") develop distal to a swollen segment of a limb. Asymmetry of strength may be a subtle early indicator: Weakness of dorsiflexion of the foot, for instance, may herald increasing pressure in the anterior compartment of the leg.

A Doppler flow probe will be a crucial diagnostic modality to aid physical examination on space station.

#### **INITIAL MANAGEMENT**

Following hemostasis, the first consideration in management of limb injury is reduction of dislocated joints and severely displaced fractures with which might be associated significant neurovascular compromise. The second consideration is to splint identified or suspected fractures in order to provide comfort and prevent injury to adjacent structures by motion of fracture fragments.

When an obvious dislocation or grossly displaced fracture is identified on physical examination, decision must be made whether to attempt immediate reduction or to immobilize the limb and defer manipulation until roentgenograms have been obtained. Two imperatives impose upon the surgeon regarding this decision: In general, all dislocations should be reduced at the earliest feasible time. Several sequelae related to delayed reduction have previously been stated. However it is also preferable to perform roentgenography prior to manipulation of a skeletal injury, in order to : (1) document the original injury; (2) look for a fracture which might be associated with a dislocation (or vice versa); (3) provide guidance for more accurate reduction efforts.

If the limb distal to a skeletal injury is not anesthetic or ischemic, splints should be applied and manipulation avoided

until roentgenograms are obtained. Even if the limb distal to a skeletal injury is anesthetic, or ischemic as judged by the 6 "p's" criteria previously stated, yet a portable x-ray machine is immediately available, it is probably worth the brief delay involved to radiographically define the original skeletal injury.

However, if the limb distal to a dislocated or grossly displaced skeletal injury is clearly anesthetic or ischemic or both, and a portable machine is not immediately available, then attempt at immediate reduction is indicated.

At short interval after joint dislocation (before associated muscle spasm becomes severe) or in an unconscious or stuporous patient, reduction without analgesia may be possible. More often, titrated intravenous administration of an analgesic such as morphine or meperidine, with or without supplemental injection of local anesthetic, will be needed to accomplish reduction in an alert patient.

## **CRITIQUE OF DIAGNOSTIC CRITERIA AND INDICATIONS FOR SUBSEQUENT STUDIES**

### **Skeletal Injury**

The signs and symptoms by which a fracture or dislocation is suspected are not specific: Deformity and pain may be due to soft-tissue damage instead of skeletal injury. Distal neurovascular compromise may be due to primary nerve and vessel injury without fracture or dislocation. Limitation of motion may relate entirely to pain or proximal impairment of innervation. In the unconscious or stuporous patient a large amount of information is unavailable because local pain, distal light touch sensation, and active range of motion cannot be assessed. However in the multiple-trauma victim, any of the complaints or findings by which fracture or dislocation should be suspected constitutes sufficient indication for plain film x-ray study of the appropriate components of the affected limb.

The appropriate components include the joints proximal and distal to a potential long bone fracture, and the supporting bones proximal and distal to a suspected joint injury. Two views are almost always desirable and occasionally a third view, special angle, or stress film is needed. Consultation with an orthopedic surgeon or/and radiologist may be necessary both for determining what x-rays should be taken, based on symptoms and findings, and for interpretation of digitally transmitted images, as will be described in the section on radiologic imaging.

### **Tendon and Peripheral Nerve Injury**

In the alert and cooperative patient, the functional assessment of active limb motion and sensation represents both a straightforward and accurate means by which to diagnose significant injuries to tendons and nerves. In the unconscious or stuporous patient this initial data base will be incomplete

since assessment will be limited to observation of spontaneous motion and withdrawal from noxious stimuli. Operable tendon or nerve injury is extremely unlikely in the absence of a laceration or penetrating wound. Possible exceptions include: (1) joint dislocation, which may mechanically block motion, avulse an adjacent tendon insertion, or impinge upon an adjacent nerve; and (2) a closed displaced fracture, which may lacerate an adjacent nerve or tendon from within.

### **Vascular Injury**

While the probability is low of sustaining operable vascular injury in space, if such injury should occur, the risk is high of suffering otherwise preventable loss of limb if an accurate diagnosis and timely intervention cannot be achieved.

With trauma to bones and joints, nerves, and soft tissue of the limbs, significant injuries are usually readily determined by physical examination or suggestive findings lead to immediately available non-invasive roentgenographic study by which a definitive diagnosis is established. Unfortunately the same does not so frequently pertain to significant vascular injuries.

Bleeding may be relatively minimal or absent in the presence of a significant penetrating or blunt vascular injury. With complete transection of an artery, constriction and retraction of the muscular vessel ends may markedly restrict or stop bleeding. With thrombosis and intimal flap formation associated with compression/contusion injuries, a limb may quickly be jeopardized with no evidence of bleeding or hematoma.

Conversely, the presence of (nonpulsatile) bleeding with a penetrating wound or soft-tissue injury, or of a hematoma, is not specific for major vascular injury: The external bleeding or hematoma formation may well be due only to smaller vessel injury associated with extensive soft tissue damage. Similarly, a major fracture or dislocation may be present without any injury to vessels or compromise of perfusion.

Even the 6 "p's" are not infallible: Pulses distal to significant arterial injury have been present in up to 27%, and normal in 10-15%, of patients in various series. Pallor does not always develop with arterial insufficiency, and is difficult to appreciate in dark-skinned patients. If there is a concomitant venous injury, the limb is likely to appear cyanotic rather than pale. Skin temperature may be maintained if there is sufficient collateral flow and superficial vessels are dilated, or if the ambient temperature is high enough. Pain may rapidly subside and a limb become anesthetic when ischemia is severe. Paralysis and paresthesia are late signs of severe ischemia to distal muscles and motor nerves, and to peripheral sensory nerves, respectively, and therefore are not very helpful in early diagnosis. Paralysis and paresthesia may also result from direct injury to motor and peripheral sensory nerves. In addition to these specific limitations, many of the foregoing signs and symptoms may appear

as a result of hypovolemic shock and/or severe cold exposure, in the absence of arterial injury.

As previously mentioned, a bruit is a rare early finding, present only in the minority of acute vascular injuries.

A confusing factor is the question of spasm: as a relatively rare event, temporary segmental narrowing of an artery may be observed as a result of sustained local constriction of vascular smooth muscle without definable damage to the vessel. In the trauma setting when such "spasm" persists, it is dangerous not to suspect underlying injury.

Thus given: (1) the nonreliability and nonspecificity of the symptoms and findings upon which diagnosis of peripheral vascular injury is classically based, (2) the potential of limb loss as a consequence of delayed recognition and delayed surgical correction of a significant arterial injury, and (3) the desire to avoid unnecessary exploratory surgery; an ancillary study is needed by which to accurately assess the status of limb circulation in patients with suspected vascular trauma. Arteriography, preferably by the percutaneous Seldinger method, has become clearly established as the single most accurate diagnostic modality for evaluation of vascular trauma. It is of particular value in identifying or excluding operable injuries in cases where the clinical evidence is not conclusive. The value of this distinction in the space station environment has been emphasized in the discussion of other injuries.

Arteriography can: (1) precisely locate a site of contrast extravasation from a laceration, (2) identify a level of occlusion, (3) define an intimal flap obstruction, (4) demonstrate a false aneurysm or arteriovenous fistula, (5) evaluate the status of collateral circulation, and (6) help differentiate segmental spasm from true occlusion (although it may be difficult to be sure whether segmental narrowing is due to spasm rather than intimal injury).

For the reasons just given, an arteriogram is usually of great value as a preoperative "road map." Therefore, in general, in a patient with suspected vascular trauma, a preoperative arteriogram should be omitted only when: (1) the presence and location of an arterial injury are essentially certain, as in a penetrating wound with brisk bleeding or expanding hematoma; (2) it is determined that anticipated delay in obtaining the study may jeopardize limb survival, or (3) coexistence of lifethreatening thoracoabdominal or head injuries mandates immediate removal to surgery. Even in these instances, consideration should be given to obtaining a preoperative or intraoperative arteriogram on the operating table. (The operating table should always be configured for x-ray during peripheral vascular surgery in that postrepair arteriogram is often very helpful in confirming a successful result.) In the multiple injury setting, upon completion of physical examination and urgent studies such as chest x-ray, ECG, and peritoneal



lavage, priority of peripheral arteriography is secondary only to that for radiographic studies related to rapidly life-threatening thoracoabdominal and head injuries.

The technique of choice for space station will probably be digital subtraction angiography. Images can be processed remotely, and recreated on multiple viewing screens for simultaneous review by onboard physician and terrestrial consultants.

## **FRACTURE MANAGEMENT**

Both immediate and definitive management of most fractures on earth consists of external immobilization by traction or/and splinting. The same is likely to be true for space station or lunar base. Post fracture deformity is as much or more a function of adjacent muscle spasm than of gravitational force, as evidenced post femur fracture by the deformity of a thigh despite horizontal support of the entire lower limb. Therefore a mechanically adjustable or spring loaded traction device, suitable for application in absence of ability to "hang" weights, will be desirable.

For most fractures, traction is unnecessary or represents a temporary means of effecting stabilization and preventing contraction until more definitive fixation can be achieved. For most fractures, that fixation is with some form of external splint. Desirable characteristics of splints, particularly for space station or lunar base, are versatility, adjustability, light weight, and strength. Casts are infinitely "adjustable," but, depending upon the material, do not always satisfy the other criteria. Most casting materials come in a "dry" form to which (separate) water must be added for activation; some, like standard plaster, "drip" during application. Newer plastic materials, appropriately packaged as regards fluid containment, might be suitable for activation and application in a zero-G environment.

Braces with outer shells and adjustable inner bladders satisfy most of the criteria; they are likely to be heavier and bulkier to store prior to use than casting material.

External fixation devices which attach to pins drilled into bone adjacent to a fracture meet all the requirements, and allow definitive management of a number of fractures which do not respond well to application of a simple external splint and would otherwise require open reduction and internal fixation, or prolonged traction.

Early open (surgical) reduction and internal fixation has become the treatment of choice for an increasing number of closed fractures in recent years. Early exploration, debridement, and repair has long been advocated for open fractures and open joint injuries. However, injuries for which surgical intervention is indicated are rarely limb threatening, they are likely to

represent the minority of fractures sustained on space station or lunar base, and their surgical interventions can often be delayed for a number of days with a satisfactory outcome. However, a sense of complacency regarding the need for early and vigorous debridement and irrigation of open fractures and joint injuries is not to be encouraged. Although with early administration of antibiotics, delay up to 6 hours is probably without significant difference in outcome of most cases, delay in debridement of such wounds beyond 12 hours is unquestionably fraught with a distinctly higher incidence of long-term infection despite use of antibiotics.

In some cases, inability to perform relatively simple fracture surgery onboard could result in an undesirable outcome or force an otherwise unnecessary early return to earth. In most cases, the ability to apply an appropriate splint or cast will constitute definitive care. The key to appropriate decision making, as has been emphasized previously, is appropriate radiographic imaging, coupled with appropriate remote specialty consultation.

The key question to be answered for each fracture will be: can it be treated on site, or must it return to earth? It is anticipated that for most sprains and simple fractures, definitive splinting or casting will allow full treatment onboard with a goal of return to duty. In zero-G, once a sprain or fracture is immobilized, it should be possible to mobilize the patient immediately. The skeletal demineralizing effects of zero-G, as regards fracture healing, are yet to be defined.

#### **PERIPHERAL VASCULAR INJURY MANAGEMENT**

In general in terrestrial practice, a penetrating wound near the course of a major artery, or a closed limb injury, in a patient whose physical examination and angiogram are even suspicious for arterial injury, are sufficient indications for early surgical exploration. This is because, as with life-threatening injuries to head, neck, and trunk, time is a factor in successfully dealing with limb-threatening arterial injuries. It has been demonstrated that when vascular repair is undertaken within 6 hours of acute arterial occlusion, the incidence of subsequent gangrene and amputation approaches zero; while when delay in repair exceeds 12 hours, the incidence approaches 30% or more. When arterial injury is associated with a fracture or dislocation, delay in repair results in a several fold increase in late amputation rate. These time frames clearly press even the most rapid recovery intervals from LEO currently projected.

On the other hand, once the potential of exsanguinating hemorrhage has been controlled, a vascular injury might present no immediate threat to life or limb. This may be true even in the absence of distal pulse, when good capillary filling and Doppler ultrasound verified distal flow are present, and paresthesia and paralysis are absent. (It should be noted that apparent skin viability does not necessarily correlate with

viability of more perfusion-sensitive underlying muscles and nerves.) In the multiple-injury setting, trauma to other systems may deserve more immediate attention. In this event, it is important to verify, by repeated close interval" reexamination, that the vascular injury indeed continues to remain non limb threatening. Further, success of vascular trauma surgery has been shown to correlate well with the peripheral vascular reconstructive experience of the surgeon.

For these reasons, identification or strong suspicion of a major vascular injury will mandate early consultation with the appropriate remote specialty consultants as regards plan of management. Emergent recovery, possibly in an anticoagulated state, even with significant time lapse, may be preferable to undertaking a technically demanding procedure with minimum surgical assistance or blood bank support available. Angiographically guided selective embolization of bleeding vessels may also be of benefit as a life saving measure in some cases.

### **TENDON, NERVE AND SOFT TISSUE INJURY MANAGEMENT**

Delayed repair of tendons and nerves, after local wound debridement as indicated, will be acceptable management of injuries to these structures occurring on space station, just as on earth. Unless rapid recovery is conveniently available, presence of a large soft-tissue defect, major skin loss, a grossly contaminated wound, or a significant mass of devitalized muscle all represent indications for early surgical debridement. Strong suspicion of developing compartment syndrome is sufficient indication to perform fasciotomies. These are procedures for which both the space station operating facility and the surgeon onboard should be prepared.

Compartment syndrome, and ischemic muscle necrosis due to progressive infection, both represent complications of soft-tissue trauma which are truly limb threatening secondary to progressive ischemia. Since the perfusion deficit is usually an evolving one rather than of abrupt onset, the threat to limb survival is usually less immediate than that of an acute arterial occlusion. However once well under way, there is no reconstructive surgical procedure by which these processes may be effectively reversed, only ablative surgery by which to attempt to remove diseased tissue. Therefore when fasciotomy or wide debridement of devitalized muscle are indicated, early surgical intervention should be undertaken onboard, even if subsequent recovery to earth is anticipated.

## THERMAL AND ELECTRICAL BURN INJURIES

A probable incidence of burn injury on space station or lunar base is difficult to project. It is true that the only "operational" mortalities in the U.S. space program to date were sustained in a capsule fire on earth. It can also be noted that ambient cabin atmosphere is no longer 100% oxygen, and that, due to lack of convective gravitational forces acting on gases of different densities, it may not be possible to sustain an open flame in zero-G. While these observations may be reassuring, it must further be noted that the most likely burn danger in space will not be from contact with a stationary open flame, but rather from explosions of volatile gases, chemical spills (difficult to control in zero-G), and contact with electrical circuits. Relatively low power circuitry may reduce this latter risk. If space station assembly involves welding, there will be some risk of injury from both open flame and direct contact with hot metal. The mind set associated with construction and repetitive maintenance activities, in contrast to operational tasks, increases the probability of burn-producing accidents. Nuclear submarine data may not be predictive because, while submarines are assembled and serviced in port, the space station must be (at least partially) assembled and maintained in space. In fact, burn injury might well be the most likely major trauma risk in the space environment.

In any event, it must be recognized that the occurrence of a major thermal injury on space station or lunar base would present a catastrophic management challenge to medical officers and associated crew members: So much so, that the first approach to thermal injury in space must be that of prevention, both in terms of station design and operational protocols as well as flame retardant clothing, airflow control, and fire extinguishing capability.

### CLASSIFICATION AND TRIAGE DECISION

Once a thermal injury has occurred and airway and vascular access have been secured, appropriate management is guided by an accurate assessment of the magnitude of the injury. In this regard it is convenient to refer to the American Burn Association's 1976 classification of severity of thermal injury. This includes the following:

#### A. Minor Burn Injury

- 2° burn <15% total body surface area (TBSA), adults
- 2° burn <10% TBSA, children
- 3° burn < 2%, excluding the following: burns involving eyes, ears, face, hands, feet and perineum; electrical injury; inhalation injury; burn injury complicated by other major trauma; burns in poor risk patients.

B. Moderate Burn Injury

2° burn of 15-25% TBSA, adults

2° burn of 10-20% of TBSA, children

3° burn < 10% excluding the following: Burns involving eyes, ears, face, hands, feet, and perineum; electrical injury; inhalation injury; burn injury complicated by other major trauma; burns in poor risk patients

C. Major Burn Injury

2° burn >25% TBSA adults

2° burn >20% TBSA children

3° burn >10% TBSA

All burns involving hands, face, ears, feet and perineum; all patients with inhalation injury; electrical injury; burn injury complicated by other major trauma in poor risk patients.

Functionally in the space station or lunar base environment, it will probably be convenient to divide burn injuries into 3 categories:

1. Burns that likely can be treated successfully on site, with the patient continuing work duties or returning to work within a few days to a few weeks. Hopefully almost all minor and some moderate burns will fall into this category.

2. Burns which unlikely can be treated successfully on site, or which will require a prolonged interval off work in convalescence, but which should survive if treated in a recognized burn center on earth. These patients should be appropriately resuscitated on site, and terrestrial transfer effected at an early convenient interval. Hopefully the remainder of the moderate, and most major burns will fall into this category.

3. Burns which unlikely can be treated successfully in any environment, including recognized burn centers on earth. These patients should, by prior protocol agreement, be allowed to mercifully expire on site, and be returned to earth non emergently at a convenient time. Patients with 80-100% mostly full thickness burns currently fall into this category. Burn size alone is not the only criteria, however, since young people with even 80-90% partial thickness injuries frequently survive in major burn centers, while older people with 20-40% TBSA damage have a very poor prognosis.

For patients whose injury assessment makes it uncertain as to whether they should be placed in functional category 1 or 2, an important question is which way to lean. With regard to overall medical care preparation, the concept of full capability has been stressed. Historically, on earth, rural community physicians often elect to treat locally rather than incur the delay, hassle, expense, and risk of transfer. Certainly availability, cost, and safety of transfer will be influencing factors on space station. However a more important factor influencing this decision needs

to be consideration of the resources required to deliver appropriate care on site. In dealing with thermal injury, the magnitude of these resources can be staggering relative to other trauma care. While decision to transfer major Burns is not in question, it is instructive to review some of the requirements to successfully manage a previously healthy 24 year old male who sustained a 50% TBSA burn, 24.5% being full-thickness. He required 25 days of hospitalization and the following medical resources:

Surgeon - 25 hours	Blood Tests - 225
Nursing Staff - 600 hours	Blood Transfusion - 18 units
Physical Therapy - 50 hours	Plasma - 11 units
Social Services - 25 hours	Surgical Operations - 4
Dressings (Kerlex) - 558	Saline Solutions - 48 liters
Topical Antibiotic - 66 (pint) jars	

Excision and grafting of large burn wounds requires several surgical team members working simultaneously and rapidly to limit loss of blood and body heat. In most hospitals on earth, care of a single major burn patient outside a burn unit on a regular surgical ward imposes a major strain on supply lines, nurses, and maintenance personnel as regards stocking clean dressings, performing frequent dressing changes, and disposing of contaminated dressings. These problems almost certainly would be multiplied several fold in the space station environment.

#### **TIMING OF TRANSFER**

For those patients for whom early terrestrial transfer is indicated, an important question is just how "early" that transfer needs to be. Fortunately, once airway is secure and adequate fluid resuscitation is underway, the majority of (even major) burn patients should be remarkably hemodynamically stable. The burn wound itself is usually not of major consequence during the first 4-5 days following thermal injury. Beyond that, problems related to infection and natural wound separation become of paramount importance. Thus a transfer window of several hours to several days is acceptable. This has been conclusively verified in the extensive experience of long range (usually air) transfers of patients from rural community hospitals throughout the Intermountain West to the Intermountain Burn Unit at the University of Utah, and from around the world to the Brooke Army Burn Unit in San Antonio.

However a transfer delay of 14-21 days, to await arrival of the next scheduled shuttle, would seriously jeopardize a major burn patient's outcome as regards both results of skin grafting, and potential mortality from sepsis. Such a delay would also, as previously illustrated, exhaust both the medical care team and

supplies. In contrast to the non thermal major trauma patient's frequent course of early instability followed by steady recovery, the major burn patient's potential course is more likely to be that of early stability followed several days later by complications. Thus a major burn may represent one of the rare indications for early evacuation by a MOSES (Gemini) capsule, in absence of availability of a shuttle within a few days.

Just as has proved so important in the regionalization of burn care in the U.S., a key component in the management of thermal and electrical injuries on space station or lunar base will be ready access, of the mission control flight surgeon and the onboard surgeon, to consultation from burn surgeons at selected regional burn centers throughout the country. Assessment of extent of injury, initial resuscitation efforts, and treatment versus transfer decisions should be carefully coordinated with these specialists. Ideally these same burn specialists should be integrally involved from the start in the planning for preventive measures, immediate onboard treatment capabilities, and terrestrial recovery mechanisms for thermal and electrical injuries.

## **RADIOGRAPHIC IMAGING**

If the goal in medical management for space station or lunar base is full capability, then the only acceptable goal for radiographic imaging is full capability. However, even short of full medical management capability, a maximum radiographic imaging capability can be justified in dealing with trauma and emergency surgical problems. This is because with these diseases, so many of the diagnoses and, hence, so many of the management decisions hinge upon radiographic information. As has been previously and repeatedly emphasized, in the absence of timely and accurate information, there is high likelihood of one of 2 errors: A problem will be "missed," with the delay in recognition translating into untoward medical outcome; or a problem will be suspected, with inability to conclusively affirm or disaffirm translating into an unnecessary unscheduled recovery to earth. In either case there are likely to be undesirable financial and political consequences. The cost of these consequences, in a program as publicly visible as space station or lunar base will be, could be of such magnitude as to easily be able to justify the technical effort to "do it right" the first time around.

### **EQUIPMENT: CHARACTERISTICS DESIRED; DEVICES AVAILABLE**

Desirable characteristics of diagnostic imaging equipment for space station or lunar base application include the following: (1) It should be simple, reliable, low cost, compact, light weight, and have relatively low power requirement: These, of course, are desirable qualities of current shuttle payloads. (2) It should be "user friendly:" This is particularly important during early (category 1 and 2) space station activities, when it can be anticipated that there will be no radiologic expert and possibly no physician present to operate the equipment. (3) It should be extremely reliable, with a projection of essentially no "down time:" This is important, as it can be anticipated there will never be a radiologic equipment repair technician on board. (4) It should have the broadest application and ability to provide the most data as regards ability to effectively image a maximum number of body parts with a minimum of "outside help:" A technique specific for a few problems will be of less value than one which can potentially diagnose many. (5) It should generate images which can be readily reproduced for interpretation at remote sites on earth, as well as viewed on board.

Relative to these desirable characteristics, it is instructive to critique the characteristics of current terrestrial hospital and clinic imaging equipment. Unfortunately it fails to measure up in most respects. It tends to be complex, expensive, bulky, heavy, and have a relatively heavy power requirement. Most devices are not particularly user friendly, having been designed for use by radiologic technicians. Particularly bothersome is the reliability issue, with too high a ratio of maintenance to operational hours (although fortunately nowhere near that of military aircraft avionics units). Most devices provide



incomplete information and imperfect resolution of images, with the consequence that the findings on one study often prompt recommendation for further imaging by another modality.

One desirable feature which is achievable with all current generation devices is the ability to reliably transmit and reproduce images over long distances without a wire link. In U.S. experiments using satellites and ground microwave relays, such transmission-reproduction has been judged to be quite satisfactory and diagnostic. In the Canadian experience, such transmission, coupled to remote radiologic diagnostic consultation services, has become a part of the day-to-day practice of medicine in outlying communities over the past decade. Therefore current state-of-the-art can provide the capability for diagnostically accurate transmission and reproduction of the images of essentially any current modality with possible exception of nuclear magnetic resonance (NMR). Indeed it is likely that international radiology conferences will soon be held by satellite link of a number of groups, each assembled on their home soil.

Should the fact that most existing radiologic imaging equipment has unfavorable characteristics, relative to those desirable for space station or lunar base application, discourage space station planners from pursuing the goal of maximum imaging capability? Absolutely not, was the unanimous opinion of the conferees. While it will be beneficial to sequentially match the complexity of imaging equipment to the increasing complexity of the space station as it progresses through categories of development, no imaging modality should be timidly excluded from advance planning because its current terrestrially oriented embodiment is less than ideal for space application. Instead, the surgical, medical, and particularly radiological consultants should put the ball squarely back in the medical imaging design engineers' court by carefully specifying, for each imaging modality, what is desirable and acceptable as regards size, weight, power usage, complexity, reliability, and, even cost. It will become the engineers' problem to determine how to satisfactorily miniaturize the packaging of, for the most part, existing technology, and how to do it at the right price.

Two factors should encourage satisfactory solution of this problem. First, the exponentially accelerating use of computer enhancement, reconstruction, storage, and recall of images has made possible in the last few years things which were not previously possible. In fact, we have probably barely scratched the surface of the abilities of such enhancement to even more precisely reconstruct and present ever finer details of anatomy and even dynamic biochemical processes. Since current transmission capability allows accurate processing of data remotely, then there is a requirement only to miniaturize the scanning head: The computer enhancement and manipulation can be accomplished on earth rather than onboard space station, eliminating the need for space, power, repair capability, etc. for those components of the imaging system. This should reduce

size and cost and improve reliability.

Second, this sort of equipment redesign is the kind of challenge to which high tech engineering, world wide, has previously demonstrated an amazing capability to respond, provided an appropriate market is visible. While a few units for space station or lunar base do not constitute such a market, thousands of emergency rooms, operating rooms, intensive care units, and clinics all over the world do. It is not unlikely that the medical equipment requirements for space station, if boldly stated, could trigger another round of "spin-off" benefits, worth to the economy and to the quality of future medical care many fold the cost of initial development, much as resulted from the decade of the Apollo program. The medical community should assert that this bold vision is desirable.

Historically, it is of interest to note that necessity, associated with the house call mode of earlier medical practice, was, indeed, the mother of invention of a portable x-ray machine used by physicians in patients' homes during the first quarter of this century. The quality of images was low and the scatter of stray radiation was high, but the device satisfied a diagnostic requirement. With increasing hospital basing of practice and increasing standards of radiation safety, production of these portable devices yielded to that of large, fixed machines of higher quality. As x-ray usage increased in special care settings such as emergency rooms, operating rooms, and intensive care units, there again developed a demand for "portable" x-ray machines. But since these have only to maneuver through hospital corridors via motorized carriages, weights of 500 pounds are common. The cumbersomeness of these machines and inability to view all angles conveniently, plus increased use of diagnostic imaging in guiding performance of various procedures, has encouraged the development of another generation of truly portable devices. The Lixiscope (TM) represents an example of this next generation.

#### **PRIORITIZATION OF IMAGING MODALITIES**

As regards matching the complexity of imaging equipment to the developing complexity of the space station and to the background of personnel on board, the following sequence of introduction would be reasonable based on ability to miniaturize current technology:

- plan x-ray with fluroscopic imaging capability
- computer assisted tomography (preferably total body)
- digital subtraction angiography, or
- ultrasound
- nuclear medicine
- nuclear magnetic resonance (NMR)

#### **Plain X-ray**

Plain x-ray can satisfy most of the desirable characteristics.

It can be made locally user friendly, and, except for the head and vasculature, can provide good definition over most of the body.

## **CT**

Total body CT, with a relatively light scanning head and remote image reconstruction is probably next on the list because of its tremendous versatility and range of diagnostic capability all over the body, and because with totally remote processing and interpretation, the mechanics of operating the scanning head could be made very user friendly to personnel with very limited training.

## **Digital Angiography**

Digital angiography requires establishment of some degree of vascular access (minimal if the injection is intravenous), but, again with remote processing, performance can otherwise be made to be with minimum requirement for special radiologic skill. It provides information critical to certain diagnoses which is otherwise unavailable with plain x-ray or CT.

## **Ultrasound**

On first consideration, ultrasound might appear to be an ideal modality for space station applications: the equipment is light, compact, relatively simple and requires low power. However the quality of diagnostic imaging is highly "operator dependent." In hospital practice, on the same patient on the same day, one trained operator may be able to obtain a meaningful study while another may not. In addition, it has no application in the chest, a common area of interest, and little application in the skull. Its introduction should await the frequent presence of an appropriate operator.

## **Nuclear Medicine**

Nuclear medicine is well down the list not for a characteristic of local operator dependence, but for its limited and overly organ specific capability, plus anticipation of unavailability on a routine basis of many short half-life isotopes.

## **NMR**

NMR resides at the bottom of the list only because the full capabilities of this emerging technology are not yet defined, and because current generation equipment requires very large mass, bulk, power consumption and capital expenditure. Yet as an imaging modality per se, NMR, coupled with computer manipulation of signal, is projected to be able to provide a more complete definition of anatomy throughout the body than any other technique. In addition, it is projected to be able to provide a measure of metabolic activity in many tissues. This may have very important implications as regards ability to accurately

document processes of adaptation to long term exposure to zero-G. Thus it may better satisfy the goals of versatility and broad application than any other current modality or projection thereof.

Like CT, remote computer signal processing should allow construction of a relatively user-friendly NMR scanning head requiring minimal operator skill and minimal onboard maintenance. While creation of a satisfactory magnetic field in current generation machines on earth requires a very large scanning head and power supply, these requirements might be markedly reduced with ability to use perpetually super-cooled metals in space.

### **Role Of The Radiologic Consultant**

An important consideration is who will be selecting and interpreting the medical imaging. In current terrestrial practice, most clinicians become comfortable with and competent in selecting and interpreting, but usually not performing, a narrow spectrum of radiographic studies relating to their area of specialty practice. They usually are neither comfortable with nor competent in the wider spectrum of common studies outside their field, or even in the newest studies or modalities in their own field. Therefore it would appear that appropriate medical imaging goals for space station and lunar base will include the following: (1) Physicians and non physician crew members should be adequately trained to perform radiographic studies using equipment specifically designed for maximum user-friendliness and minimum operator dependence as regards quality of images. (2) A cadre of radiographic specialty consultants on earth, with appropriate voice, video, and CRT data presentation links, should be available to actively participate in the selection and interpretation of the studies performed by these personnel with minimum radiologic training. (3) The mission control flight surgeon should be able to rapidly access these radiology consultants as the flight surgeon or onboard surgeon perceives the need.

Another intriguing consideration is that of a requirement for a preflight total body CT scan, with computation and archival storage of all baseline tissue densities, and identification of any significant anatomic anomalies which might predispose to certain diseases or complicate their management. Certain defects, perhaps such as urinary tract anomalies and vascular malformations, might represent sufficient criteria for disqualification. In the event of disease or injury, a comparison of an onboard scan with the baseline density data for corresponding tissues might permit earlier diagnosis of subtle problems. A similar comparative capability is likely to develop in terrestrial practice. With increase in accuracy and decrease in radiation dosage anticipated for future CT scanners, it is not difficult to imagine the day when most babies born in the U.S. will have postnatal CT scans performed to constitute a part of their permanent medical records.

## CRITICAL CARE

While space station and lunar base represent frontier experiences, it is unlikely, with exception of the massive burns just discussed, that participants will enter into "arctic explorer's pacts" of agreement to be "left behind" to die in the event of injuries or illnesses of a certain magnitude. First, it will not be necessary because the infirmity of one is unlikely to threaten the survival of others; second, it will not be politically possible on "frontiers" as publicly visible as these programs. In fact, it is likely that public attitudes toward care in space will parallel those on earth. In the event of catastrophic multiple casualties, triage and prioritization of care will be expected and accepted. However, for an individual injury or illness, the attitude after, if not before, the occurrence more likely will be that no price is too great to save a life if it is technically possible to do so. The more critical the illness or injury, the more critical will be the care that is "expected" to be delivered. More so than other emergency care, the capability to sustain delivery of critical care will require prior planning and organization. That planning and organization should be guided by the following considerations.

In addition to major trauma and thermal injury, consideration must be given to management of decompression pneumothoraces, pneumonia, peptic ulcer with perforation, obstruction, or bleeding, blood loss from other gastrointestinal or extra-GI sites, electrical injuries, and sepsis from a variety of sources. Younger crew members may be more susceptible to some of these events: pneumonia, for instance, may occur more frequently in the third decade than later, presumably because of lack of previous exposure to the virus.

Accurate diagnosis and evaluation of effectiveness of intervention for a variety of conditions will require appropriate radiographic imaging capability, as already discussed, and appropriate clinical laboratory capability, as will be discussed.

Even for a critical patient, immediate retrieval to earth, while possibly desirable, for planning purposes must be considered impossible or impractical. It must be assumed that there will be some interval during which intensive care must be delivered onboard, either because the patient's condition is too unstable for transfer, or an appropriate transfer vehicle is not immediately available, or both. "Windows" of time appropriate for transfer, as have been discussed for major burn cases and as will be discussed for sick people in general, will apply to critically ill and injured patients. As long as there is some capability to deliver care onboard, most physicians will likely be unwilling to immediately commit a critically ill patient to terrestrial recovery via a MOSES Gemini capsule type vehicle: the obvious risk to both patient and health care worker will probably be judged to outweigh the potential benefits.

Ability to deliver appropriate care will parallel availability of appropriate equipment, and the ability of crew members to correctly use that equipment. Under remote supervision of a critical care physician, non physician astronauts, trained to the level of advanced EMT skills, should be able to orally intubate the airway and ventilate the lungs, nasally intubate the stomach and aspirate contents, and transurethraally intubate the bladder; they should be able to cannulate peripheral veins and control intravenous solution infusion; they should be able to apply ECG monitors, operate defibrillator paddles, and perform CPR. Therefore, even during category 1 and 2 space station development, it would be reasonable to plan to have equipment present with which to accomplish these maneuvers.

An important factor to consider is the phenomenon of skill decay in the absence of either extensive prior experience or opportunity to maintain facility by frequent current performance. It is well recognized, for instance, that EMT-A's in rural areas more quickly loose their adeptness at cardiopulmonary resuscitation than do individuals of comparable initial training who practice their skills more frequently in an urban setting. However, even in absence of current practice, a physician with extensive prior experience in resuscitation would not be expected to suffer significant decay in performance capability during a several month space station or lunar base "rotation."

When physicians are first included as regular crew members for space station or lunar base, it is assumed those physicians will probably be surgeons, not critical care specialists (although the 2 areas are by no means mutually exclusive). Since one of the main roles of "intensivists" has become that of orchestrating and integrating care, the most appropriate role for critical care physicians will be that of specialty consultation, immediatly available on call to the mission control flight surgeon and the onboard surgeon.

Even more so than with other specialty problems, successful critical care consultation will require reliable rapid contact, and ability to communicate data. As previously described, this communications requirement translates into a need for audio, video, and computer CRT equipment, with terminals situated within the same critical care units in which selected critical care experts regularly practice.

Just as computer prompted algorithms are being used with increasing frequency to guide management according to protocols in critical care units on earth, so will computer interaction play a major role in suggesting assessments, interventions, and reassessments to the surgeon onboard and the mission control flight surgeon. The software for these interactions may not be directly transferable from terrestrial ICU programs, for, as will be discussed, it is anticipated that parameters will be more carefully selected to limit the number of variables and their frequency of measurement to those which maximize useful information. For instance, in weaning from mechanical ventilator

support, while 20 variables may be applicable, the decision is usually made based on 2 or 3. Early in space station and lunar base medical operations, it likely will be safer as well as more effective to program toward too few rather than too many variables to monitor.

As with burn care, for general medical-surgical critical care, consideration needs to be given to the numbers and kinds of personnel and supplies required to deliver particular levels of care for various illnesses and injuries. Although potentially a very imperfect analogy, comparison is likely to be made to certain nursing intervention scoring systems which have been developed by critical care personnel to document the need for those nursing staff: patient ratios of found necessary to appropriately care for particular degrees of severity of illness in ICUs. This issue of nursing definitely needs to be addressed, particularly since most physicians do not currently have a mind-set to deliver the hour after hour care needed to successfully treat many illnesses and injuries. Consideration of this component of care will be important in deciding which problems should be treated onboard versus recovered to earth, and what delay prior to recovery can be tolerated.

In recent years, nurses (particularly in critical care) have come to function in a much more physician-independent mode as regards direct patient care. The computer algorithms which guide physician assessments and interventions can do the same for nurses. Nursing personnel on space station might as easily function under the remote control of the critical care consultant as under direct supervision of the surgeon onboard.

Among resources which may be of critical importance, blood for transfusion is a key consideration. Shelf life of blood bank units is likely to remain ultimately limited by normal red blood cell lifespan. The conventional 21 day limit is somewhat arbitrary, but probably could be complied with by delivering new blood to the space station bank with each shuttle cycle. However for longer term missions or with abrupt need for additional red cell volume, and in the absence of a breakthrough in development of a safe, effective synthetic oxygen carrying substitute, the capability to draw and process blood onboard will be needed. With the body fluid shifts demonstrated in zero-G, recipient needs of the trauma victim may be increased relative to the same injury on earth. At the same time, donor capacity may be decreased: a "unit" may be too much to give up without untoward effects for the donor. Some consideration might be given to selection of blood type compatible crew members.

As was admonished in the planning for burn care, critical care physicians need to be involved from the outset in planning for the evaluation and management of critically ill or injured patients on space station or lunar base. To be most effective, this planning should include frequent direct exchanges between the critical care consultants and the equipment design bioengineers.

## PHYSIOLOGIC MONITORING

Recent studies of the value of various physiologic variables as regards prediction of outcome, particularly when the outcome criteria is survival versus non survival, reveal a distressing observation: Those variables which are most frequently measured are least predictive. The probable reason they are measured so frequently is because it is convenient and conventional to do so, not because they significantly influence changes in therapy.

When survival is the outcome criteria, knowing heart rate and peripheral vascular resistance, for instance, is much less useful than knowing oxygen consumption ( $\dot{V}O_2$ ) in relation to red cell mass and flow. In a critically ill or injured patient, reliable therapeutic goals for survival, in addition to a normal blood pressure, currently appear to be the following: cardiac output about  $1.5 \times$  normal, blood volume about normal, oxygen transport normal, and  $\dot{V}O_2 >$  normal. In prospective trials using multivariant analysis, these criteria have been found to be about 93% accurate. (Shoemaker WC, Czer LSC: Evaluation of the biologic importance of various hemodynamic and oxygen transport variables. Crit Care Med 1979; 7:424; Shoemaker WC, Appel PL, Bland R, et al: Clinical trial of an algorithm for outcome prediction in acute circulatory failure. Crit Care Med 1982; 10:390; Shoemaker WC, Appel PL, Waxman K, et al: Clinical Trial of survivors' cardiorespiratory patterns as therapeutic goals in critically ill postoperative patients. Crit Care Med 1982; 10:398.)

It is interesting to note that because of alterations in compliance of the vascular tree, blood volume in sick people does not always correlate well with the very frequently measured (right sided) central venous pressure or (left sided) pulmonary artery occlusion (wedge) pressure. This disparity may be aggravated by redistribution of body fluid in zero-G. It is also interesting to note how many minutes before death a particular variable becomes predictive. On the average, it is only about 5 minutes for ECG, 10 minutes for heart rate, and 45 minutes for blood pressure, compared to 60-120 minutes for cardiac output and  $\dot{V}O_2$ .

Given the anticipated constraints of space station, it will be important to select physiologic variables to monitor which provide maximum information relative to volume, weight, and power requirements of the measuring equipment. It also will be important to select variables whose measurement can be accomplished by the personnel present on space station.

With regard to the variables just suggested as most relevant, cardiac output and blood volume measurements, as currently performed in most ICUs, can be done with relatively compact equipment, but require (relatively simple) invasive techniques. As a noninvasive technique for cardiac output determination, ballistocardiography might prove more applicable in zero-G than it has on earth.



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Fortunately there are now several commercially available devices that allow determination of systemic  $\text{VO}_2$  and  $\text{VCO}_2$  from analysis of expired gasses. One of these, the Medicor MGM-2 metabolic gas monitor, uses a relatively simple, compact, feed back controlled gas replenishment system; is highly reliable and relatively inexpensive. Another, the Beckman Horizon Metabolic Cart, uses mass spectrometer analysis and requires measurement of expired gas flow; is relatively larger and more expensive. Whenever a mass spectrometry device is applicable to a measurement on space station or lunar base, consideration might be given to use of the infinite vacuum immediately available "outside" as a means of reducing size, weight, and power requirement of the device.

While a precise determination of oxygen transport (content x flow) still requires invasive techniques for measurement of arterial blood gasses and cardiac output, it has been demonstrated recently that noninvasive transcutaneous measurements of oxygen and carbondioxide tensions in the skin and the conjunctiva constitute meaningful substitutes for the systemic data. The transcutaneous oximetry and capnrimetry devices employ small  $\text{O}_2$  and  $\text{CO}_2$  electrodes similar to those used in conventional bench mounted blood gas analyzers. Heating elements in the sensors increase the temperature of the skin to a value several degrees greater than that of the body, in order to generate a local hyperemia and vasodilation necessary to increase gas diffusion through the skin and insulate the sensor from fluctuations associated with small local changes in flow.

A key question in transcutaneous gas monitoring has been whether the transcutaneously measured gas tension is an accurate reflection of the arterial gas tension, and under what conditions and to what extent that relationship may vary. A convenient parameter to study has been the transcutaneous : systemic gas tension ratio:  $\text{PtcO}_2/\text{PaO}_2$  and  $\text{PtcCO}_2/\text{PaCO}_2$ . In the extensive experience in transcutaneous monitoring in neonates, that ratio remains close to 1, presumably due to the small distance between surface and core blood flow, an immature peripheral vasoregulatory mechanism, and the ability to maintain a constant ambient temperature in an isolette. In adults, this ratio has been found to vary with clinical condition: When blood flow is normal,  $\text{PtcO}_2$  changes with oxygen content ( $\text{PaO}_2$ ): with hyperoxemia the ratio may be well above .9; with normoxemia the ratio may be as low as .8. When blood flow is below normal but  $\text{PaO}_2$  is adequate,  $\text{PtcO}_2$  changes with flow. Since transport = flow x content, when either blood flow, or oxygen content, or both are compromised,  $\text{PtcO}_2$  changes with transport. Thus  $\text{PtcO}_2$  will track  $\text{PaO}_2$  unless blood flow is impaired.

Since oxygen transport is of more important predictive value than  $\text{PaO}_2$ , then the potential of significant divergence of  $\text{PtcO}_2$  and  $\text{PaO}_2$  values does not have to be regarded as a liability in critical care monitoring. If, during continuous monitoring,  $\text{PtcO}_2$  significantly decreases, arterial blood can be drawn for

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PaO<sub>2</sub> determination: If PaO<sub>2</sub> is relatively unchanged, there has been hemodynamic deterioration; if PaO<sub>2</sub> has declined, there probably (also) has been pulmonary oxygenation deterioration. [Shoemaker WC, Vidyasagar D: Physiological and clinical significance of PtcO<sub>2</sub> and PtcCO<sub>2</sub> measurements. Crit Care Med 1981;9(10):689-90]

It has also been shown that PtcCO<sub>2</sub> tends to be greater than PaCO<sub>2</sub>, and the first follows the second well. Unless the cardiac index is markedly depressed, PtcCO<sub>2</sub> is less sensitive to changes in flow than PtO<sub>2</sub>.

It is of interest to note that without "the numbers," a seasoned surgeon can predict survival versus non survival of a critically ill or injured patient with about 70% accuracy; given the "standard" numbers, the accuracy of prediction by the surgeon increase to about 80%.

## SELECTION AND DEVELOPMENT OF CLINICAL LABORATORY EQUIPMENT

A minimum clinical laboratory capability for space station or lunar base should include that which is currently present within many critical care units and post anesthesia recovery rooms, plus limited hematology and blood banking functions. In particular, physicians and nurses without prior clinical laboratory training are routinely operating microprocessor based automated blood gas analyzers to measure arterial and venous pH, PCO<sub>2</sub>, PaO<sub>2</sub>, and hemoglobin saturations (with computed base excess, etc.); they are operating automated electrolyte analyzers to measure serum electrolytes. With a small centrifuge, hematocrit is also measured within ICUs; the Coulter counters for automated white blood cell counting are usually operated within the clinical laboratory. Blood typing and crossmatching has remained a laboratory function, in major centers even vested within the hands of special laboratory technicians. Serum glucose usually is reported with electrolytes.

An important issue is the selection or/and development of specific equipment with which to accomplish these measurements on space station or lunar base. Key variables have been mentioned previously: size, weight, power requirement, reliability, ruggedness, simplicity, versatility and cost. A new family of biosensor devices is currently under development which is more likely to optimize these variables than the current generation of automated gas and electrolyte analyzers, or the photoemulsion system analyzers: these are the Ion Sensitive Field Effect Transistors, or ISFETs. A brief review of principles of FET construction and biologic application follows.

### ISFET DEVICES

A transistor is a semiconductor triode, whose 3 portions: emitter, collector, and base (or gate) are comparable to the elements of a vacuum tube. The transistor can function as an amplifier, in that small variations in gate bias control fluctuations in emitter-collector current. Current in a low resistance input circuit can be transferred to a high resistance output circuit. Resultant voltage (current x resistance) amplification is thus due to impedance transformation.

In a ISFET, an ion specific polymer membrane is fabricated in direct contact with the gate insulator of a (field effect) transistor chip. The resultant chip-membrane unit is of small enough size (less than 2 mm) that it can be "packaged" on the end of a typical indwelling intravenous catheter.

In use, the catheter/probe (and thus surface of membrane) is placed in contact with the physiologic fluid of interest (blood, interstitial fluid, etc.). The Nernst potential developed at the ion-selective polymer membrane/solution interface is transmitted to the (transistor) gate. The resultant (amplified) potential generated at the transistor is proportional to activity of the ion for which the membrane is specific. This signal can be

remotely processed, and displayed as a digital read-out.

The operation can be compared to that of a conventional pH meter (or any other ion sensitive electrode) as follows: In figure 1a, the pH electrode (1) with ion sensitive membrane (5), and reference electrode (2), are connected by a shielded cable (3) to an amplifier (4). Bias input to the amplifier (6) effectively "gates" the resultant potential which is amplified and directed to a display unit (not shown). In the ISFET device, Figure 1b, the ion sensitive membrane (5) is placed directly at the input gate (6) of the amplifier (FET). The amplifier is then remotely connected to a processing control/display unit (not shown).

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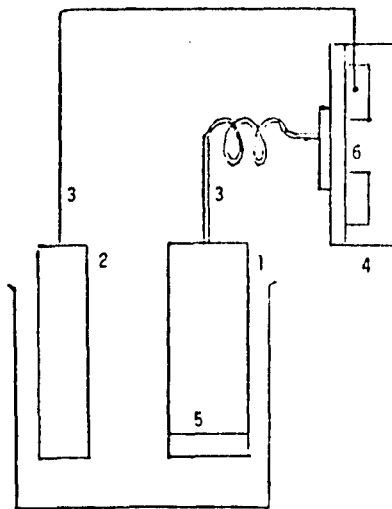


Fig 1a

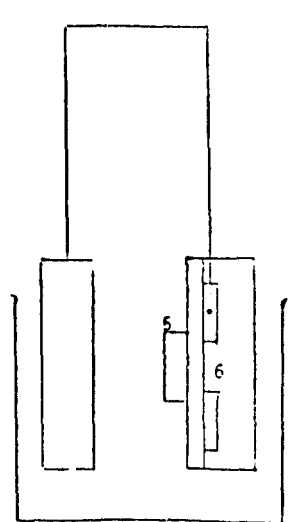


Fig 1b

In the next (developmental) step, the reference electrode is included, and the whole package is miniaturized. This arrangement has a number of advantages: The field effect transistor is an impedance transformer, which means that there is no need for shielded wires. This in turn reduces capacitive coupling and - along with small gate area and thin membrane - results in rapid time response of the whole system. Integrated circuits using ISFETs are very small, and without additional increase in size or substantial increase in price, several gates of different ion specificity can be fabricated on a single probe or catheter (e.g., pH and  $K^+$  or  $Ca^{++}$ ).

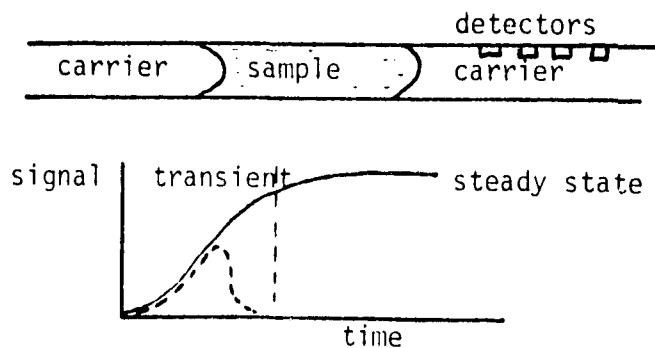
ISFET measurements are continuous, as opposed to intermittent electrolyte and pH analyses currently used. ISFETs measure actual activity of ionized species rather than total

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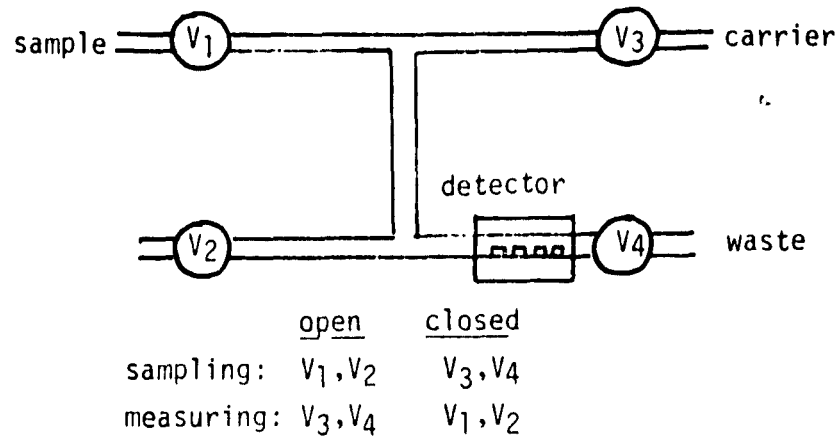
concentration. Actual activity often may be physiologically more relevant, as in the case of ions which exist in "bound" and "free" form, such as calcium. Temperature compensation can be easily accomplished by adjusting gate bias. The probes are extraordinarily rugged, and they are sterilizable. Preliminary work with pH and K<sup>+</sup> probes show they can be surface treated with heparin to discourage clot formation without deterioration of electrochemical performance. With this feature, and because of their small size, the probes can be used for continuous in vivo as well as intermittent in vitro monitoring of biologic fluids of interest. Even interstitial fluid compartments can be accessed by these devices, producing continuous measurements not otherwise possible with sensors applicable to clinical conditions. (McKinley BA, Houtchens BA, Janata J: Continuous monitoring of interstitial fluid potassium during hemorrhagic shock in dogs. Crit Care Med 1981; 9(12): 845-51)

ISFET devices have been under development and evaluation for several years by the Department of Bioengineering at the University of Utah. Species capabilities demonstrated to date include pH (H<sup>+</sup>), K<sup>+</sup>, Ca<sup>++</sup>, CO<sub>2</sub>, O<sub>2</sub>. Immediately possible are Na<sup>+</sup>, NH<sub>4</sub><sup>+</sup> and essentially any halide, X<sup>-</sup>. Theoretically possible are even enzymes (ENFETs) and hormones (IMMUNOFETs). Most biologic fluids have been analyzed, including plasma, serum, blood (under proper conditions), urine, sweat, gastrointestinal contents, etc.

The most recent chapter in ISFET application at Utah has been use of Flow Injection Analysis (FIA) as a methodology by which to use FET devices, ex vivo, to concurrently measure the activity of several ions in a very small blood (or other biologic fluid) sample. In FIA circuitry, several FET detectors specific for different ion species are mounted in a very small diameter (capillary) tube. Aliquots of sample fluid are propelled through the detector by a stream of "carrier" fluid:



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The marriage of FET and FIA technology creates chemical laboratory devices which require very small sample volumes (about 20 $\mu$ L), have rapid sampling frequencies, are easy to calibrate using very small volumes of standard solutions, are extremely flexible in terms of variety of ion and biologic fluids which can be assayed, are relatively simple, rugged, and extremely compact (the entire "laboratory" is the size of a small suitcase), and have low power requirements. These characteristics closely match those stated as highly desirable for space station and lunar base. Thus it is highly recommended that NASA further investigate the applicability of ISFET and FIA technology to development of clinical laboratory devices.

Should NASA look to ISFET technology for potential space station or lunar base application, an important consideration will be the lead time required to develop "space rated" hardware. That lead time, at an aggressive minimum, probably would be at least 2 years.

## COMPUTERIZED DATA ACQUISITION, MANAGEMENT, AND CLINICAL DECISION MAKING

Computers in critical care medicine are currently used to acquire, communicate, organize, and correlate patient data, and to assist in clinical decision making. There are a number of commercially available programs designed to accomplish the first 4 of these functions; while most of these work fairly well, most fall short in the last function. Because of the mass of data that is generated in the critical care setting today - virtually an information glut exists - the ability of computer algorithms to extract key elements for timely decision making is too important a feature not to fully exploit. The Health Evaluation through Logical Processing (HELP) system, developed by the University of Utah Department of Biophysics and Medical Computing, probably represents the most successful current attempt to comprehensively integrate and interpret medical data available from a variety of sources. These sources include indwelling continuous and exvivo intermittent physiologic monitors at the bedside, data hand entered by nurses, physicians, and other health care workers, all aspects of laboratory generated data, and historical and demographic data.

Despite more than a decade of exponentially accelerating development of computer data management programs, only recently have only a few centers been questioning what data should be generated and stored, rather than what data can be acquired. At the heavily computerized 500-600 bed Latter Day Saints Hospital in Salt Lake City, of about 430,000 Bytes of data stored per day, only about 8000 Bytes per day have been found to be recalled and "read:" This represents a write to read ratio greater than 50:1.

Even more revealing than the overall read to write statistic is a comparison of what kinds of data are used for clinical decision making, versus what kinds of data usually are being stored, thus generating the following data-category specific write-to-read ratios for the 8,000 Bytes recalled from the 430,000 Bytes stored:

<u>Kind of data</u>	<u>Fraction of total "stored"</u>	<u>Fraction of total read:</u>	<u>Ratio, stored:read</u>
laboratory	8.5%	33%	1 (too little)
drugs and fluid balance	36%	22%	about right
observations (systems review, exam, ventilatory data	6.8%	21%	1 (too little)
bedside physiologic monitors (heart rate blood pressure, etc)	32.5%	13%	1 (too much)
blood gasses	7.8%	9%	about right
other (history, ECG, x-ray)	8.4%	2%	1 (acceptable)

The implication of these observations, as regards development and/or application of clinical monitoring and decision making computer programs for space station and lunar base, is that attention should be directed to: (1) careful selection and storage of data which may make a difference in clinical care, rather than data which is convenient to acquire and store; and (2) development or selection of programs which best aid in interpreting the data for decision making, rather than to programs which maximize storage and regurgitation capability. A logical way to proceed so as to achieve the desired outcome might be to obtain input from the clinical specialty consultants with regard to what data they actually use for decision making, then allow the medical computing specialty group to develop programs that maximize acquisition and organization of that data. An ongoing relationship with a major medical center based medical computing group might be the factor most likely to insure development of software capable of interfacing with rapidly emerging technology in physiologic and laboratory sensor design.

For computing equipment aboard space station or lunar base, the usual constraints related to size, weight, power requirements, and reliability will all apply. An obvious strategy in meeting these constraints will be to transfer data from relatively small computers on board to relatively large computers on earth. In developing this link, several considerations will be important.

It will be necessary to be able to reproduce a large (although selected) fraction of the computerized data on CRTs which are located at the medical centers - often within special care units at those medical centers - within which the various clinical specialty consultants regularly practice. At each of these same stations it will be important to be able to simultaneously establish an audio-video link. Appropriate hardware will be required to simultaneously link the surgeon onboard, the mission



control flight surgeon, and any specialty consultant, or any 2 of these 3. With the additional communications satellites projected to be operational within the next decade and before space station is operational, it should be possible to establish these linkages on a continuous basis in a relatively straight forward fashion.

It will be necessary to address the problem of patient privacy, an issue with which the current astronaut corps has been more than casually concerned. While selected medical specialty consultants on earth may need rapid access to a broad spectrum of crew member medical data, both current and historical, it would be desirable if the mission control flight surgeon could limit access to selected consultants and to "need to know" components of data. The dual desires for rapidity and ease of data access when needed, yet ability to protect privacy when data access is not needed, often seem to be inherently in conflict. While this is already a well recognized problem in terrestrial electronic data management systems, the potential for abuse of accessibility could be accentuated several fold by increased use of satellite data communications systems. At the same time, a number of security solutions evolving for terrestrial electronic data management systems probably will be available in time for space station communications applications.

Extrapolating from terrestrial intensive care unit experience: While rapid 2 way data transfer between space station and earth will allow access of the space station crew to very sophisticated computer resources using only relatively modest hardware onboard, nevertheless the space station crew should be able to store and recall a relatively broad spectrum and generous volume of "commonly used" data using hardware onboard. This is important for reliability, speed of response, and crew morale. Fortunately it is very likely that advances in "microcomputing" will be more than able to satisfy these requirements as regards size, speed, adequacy of presentation, and ruggedness. The Radio Shack TRS 80 brief case computer (10"x7"x2") with 32 K byte capacity, full keyboard, mini liquid graphite screen and printer, for less than \$1000, is representative of the rapid progress in ability to package big computing power in small units at reasonable cost.

One of the most exciting areas of current advances in medical computing is the development of consultation and teaching programs capable of performing literature searches, offering differential diagnoses based on all available data, and prompting interventions relative to problems identified. Clearly this sort of resource will be very desirable for the onboard surgeon, mission control flight surgeon, and specialty consultants. As will be discussed next, there probably will be certain differential diagnostic thinking and prioritization of responses which will need to be different for space station compared to terrestrial presentation with similar symptoms or findings. In these regards, it will be important to carefully define the specific data and the logic needed to make various key decisions.

## **MEDICAL DECISION MAKING APPROPRIATE FOR REMOTE POPULATIONS IN SELF-CONTAINED ENVIRONMENTS**

Most medical decision making algorithms that have evolved in terrestrial clinical practice exhibit the following characteristics:

(1) When a patient presents with an illness or injury, the physician's priority of concerns regarding protection from harm is first the patient, then health care workers, then others who may have contacted the patient, and finally the community and its environment. The interval between the first signs or symptoms in an individual and the first action directed to altering conditions in the community may vary from hours to weeks, or, in the case of industrially generated carcinogens, this interval may well be years.

(2) In attempting to establish a diagnosis, the physician usually considers first those diagnoses which are most likely, based on the presentation, regardless of their degree of potential severity, and performs first those studies which are of least risk and most likely to affirm or disaffirm the most likely diagnoses. Only when the likely diagnoses are disproven does the physician consider less likely diagnoses and proceed to more invasive and risky studies which have less likelihood of being diagnostic based on the presentation.

(3) Very early in the process, once a working diagnosis is established, therapy may be started, both to alleviate symptoms and to gain control of an otherwise progressive problem. This is particularly true for critical illness or injury: For example, when "shock" is recognized, some treatment is usually begun before establishing the precise cause.

(4) In deciding whether and when to refer a patient to another facility, the primary physician is heavily influenced by the patient's current condition relative to the most likely diagnoses.

Experience gained in providing medical care for remote populations on earth strongly suggests that algorithms and thought processes for space station and lunar base need to incorporate decision trees whose sequential priorities proceed generally opposite to those just described:

1. When an environment is self contained and its life support systems relatively fragile, it is important to recognize that if one crew member's illness or injury might be related to an environmental hazard, then the well being of many or all other crew members rapidly may be in jeopardy. For this reason, it is important to try to identify an environmental hazard within seconds to minutes of an individual's presentation with signs or symptoms which might suggest such a cause. In such circumstances, corrective action to protect the community may need to be taken even before alleviation of the patient's

symptoms or confirmation of the diagnosis.

This imperative has significant implications as regards the need to design environmental monitoring equipment and computer based diagnostic programs which can rapidly integrate the specifics of patient presentation with potential environmental hazard data, in order to suggest potential explanations and their probabilities, confirmation options, and immediate corrective actions. Protection of the entire community takes precedence over protection and treatment of the individual. Thus, in monitoring equipment development, devices which can detect conditions likely to effect the entire crew should receive earlier emphasis than devices designed to maintain an individual's health for a unique condition which would not require evacuation.

2. When evacuation is either unnecessary, or clearly impossible, or reliably available at any hour or day it is needed, then the diagnostic efforts may be sequenced as they otherwise would be, based upon environmental concerns, and upon the patient's apparent condition versus local diagnostic and treatment capabilities. But when the patient's apparent presenting condition suggests potential need for evacuation, and acceptable evacuation is expected to be available only at relatively infrequent intervals, then the immediate diagnostic sequence cannot ignore the concept of these available "evacuation windows."

The situation in which this concept is most important is when (1) the anticipated evacuation window is narrow, as it might be on space station from the time of injury or onset of illness until the next scheduled departure for earth of the shuttle, and (2) the need for evacuation is uncertain based on initial presentation. In this circumstance it is appropriate to start the diagnostic decision tree not necessarily with the most likely problem, but rather with the potential worst case. Instead of working from the most to least likely diagnoses, one works from the most to least potentially serious diagnoses in order to most rapidly establish or eliminate the need for early evacuation. This sequence may require the early use of relatively higher risk and more invasive studies, even though they are less likely, based on initial presentation, to yield positive results. This is justified because the greater risk is failure to recognize the need for evacuation while the "window" is still open.

Experience gained in using these "reverse logic" decision trees in the medical care of remote populations suggests that it is difficult, particularly for a physician confronted with a sick and perhaps suffering patient, to immediately and concurrently consider the well being of the community as well as that of the patient, and the worst cases as well as the more likely diagnoses. It is reasonable to project that such difficulties are likely to be compounded in the space medicine environment. The intent to establish a consulting network of terrestrially based clinical specialty experts, each familiar with the environment of space station or lunar base, each with immediate

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access to computer presentation of problem data and potential solutions, all coordinated through a mission control flight surgeon, offers a means of overcoming these difficulties.

With the consulting network just described, for each episode of significant illness or injury, 3 decision trees should be initiated simultaneously: One consultant or consultation group should proceed in the usual diagnostic fashion, from most to least likely diagnoses, with primary concern for the patient's well being. Another consultant or consultation group should proceed from the most to least serious potential diagnoses, with attention directed first to identifying need for early evacuation of the patient and second to identifying risk of communicating illness to other crew. The other consultant or consultation group should evaluate potential environmental causes, with attention directed to identifying ongoing hazards to the entire crew.

The particular consultants or consultation groups will be selected by the mission control flight surgeon based on initial assessment of the problem. Each consultant or group initially will be provided the same clinical and environmental data from the onboard surgeon, mission control flight surgeon, and computer programs. Because these individuals or groups work different decision trees, it is likely they will simultaneously request different studies to affirm or disaffirm their differential diagnoses. The sequencing of these studies will be determined by the mission control flight surgeon, usually according to the following priorities: Tests which relate to the immediate safety of the environment will be done first; then, if an evacuation window is close, tests which establish or rule out more serious problems will be done next; otherwise, if an evacuation window is distant, tests which affirm or disaffirm the most likely diagnoses will be done next.

By leaving the prioritization of diagnoses and confirmatory studies to the mission control medical coordinator, each clinician and bioengineering consultant will be free to concentrate on probabilities of diagnoses, probabilities of outcomes if those diagnoses are accurate, and need for further testing relative to the priorities of those diagnoses, all within a particular decision tree. This information will be provided by the specialty experts in the form of consultation, to the mission control flight surgeon acting in the role of overall coordinator of care. Just as with any medical consultation, the mission control flight surgeon and the onboard surgeon can choose to act upon or ignore the suggestions provided, in accordance with their own synthesis and assessment of all the data.

The specialty consultant communications network suggested for space station or lunar base incorporates audio, video, and computer CRT components. Experience gained by the Indian Health Service in evaluating the efficacy of remote consultation during the STARPAC program suggests that, for experienced specialty consultants, direct voice contact is by far and away the most

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important ingredient to providing appropriate assistance to a remote primary care physician. The next most important contribution is slow scan narrow band black and white video: The major benefit of this ability to televise the primary care setting was found to be an increased level of confidence of the remote primary physician, however, and not of the consultant. Once these 2 communication links were established, the ability to transmit with clarity various diagnostic studies such as radiographs and hematology and cytology microscopic fields was perceived to contribute much less to the overall consultation than originally anticipated.

Another finding during the STARPAC program corroborates the experience of many disaster planners: Emergency consultation systems function best when they are regularly exercised. This observation has significant implications as regards the proposed medical specialty consultation network: The sooner the network is established: even if initially for solving relatively trivial medical problems on the shuttle orbiters, then the more likely the system will be able to provide the desired assistance in the event of a major medical disaster on space station or lunar base.

## **SUMMARY, CONCLUSIONS, RECOMMENDATIONS (Part 1)**

For clinical medical care on space station and lunar base, an overall goal needs to be clearly stated. As that goal, the clinical medical community in general and NASA specifically should accept nothing short of parity of quality care to that available on earth.

To achieve that goal in general, and, in particular, to successfully manage trauma and perform emergency surgery in space, a systems approach will be required. The systems approach will facilitate identification of the unknowns, and what the problems are and are not. It is often helpful to categorize the unknowns as known unknowns and unknown unknowns. It will be important to reduce the known unknowns, and to attempt to assess the impact of the unknown unknowns. The identified problems can be dissected into component parts; these can be triaged to appropriate specialists for solution. In solution of anticipated problems related to clinical medical specialty practice in the space station or lunar base environment, it will be important to seek input from clinical medical specialists and bioengineers no later than from operational medical specialists and aerospace engineers.

### **CLINICAL MEDICAL SPECIALTY AND BIOENGINEERING ADVISORY COMMITTEE**

While the observation has been made in several areas of operation that NASA has been relying too much on "inside" expertise, this admonition is particularly applicable to the area of clinical medical practice: To obtain the appropriate input on the appropriate scale to achieve the goal, it will be necessary to seek specialty expertise from the "outside" clinical medical community. For this reason the conferees recommended that NASA organize a clinical medical specialty and bioengineering advisory committee, with a charge to define and assist in the development of the necessary components of the clinical medical care system for space station and lunar base. This group of conferees are representative of appropriate individuals to serve on such a committee; most of these conferees would be willing to serve.

### **COMPONENTS OF THE SYSTEM: NEED FOR ADEQUATE LEAD TIME**

The concept of adequate "lead time" is very important in the development of successful and high quality medical care systems on earth; it is likely to be several fold more important in addressing the unique environment of space station or lunar base. While many components can be used or easily adapted "off-the-shelf" from practice on earth, the system will fall far short of its goal without special attention, well in advance, directed to development of the medical crew members, medical equipment, computerized data bank and problem solving algorithms, the specialty consultants' communications network, and to research and testing of the function and efficacy of these components.

**MEDICAL CREW MEMBERS: DERIVATION OF ONBOARD SURGEONS**

It has already been pointed out that presence of an acceptable level of surgical expertise, in absence of an opportunity to practice surgery on space station or lunar base, will require assignment, on a rotational basis, of surgeons who regularly practice surgery on earth. Further, initially instructing and subsequently updating surgeons in aspects of operational medicine is likely to be both less time consuming and more successful than attempting the reverse. These considerations imply that the appropriate clinical surgical expertise for space station or lunar base will need to be sought outside NASA.

It does not follow that the spectrum of desired expertise is currently or will be available "off-the-shelf." In fact, Dr. Trunkey pointed out that most "general" surgery training programs in this country are not turning out general surgeons in the classic sense, and most surgeons in practice tend to limit their exposure to selected diseases or anatomic areas in which they are "comfortable" (professionally and financially). In particular, the training of general surgeons in the overall management of trauma has suffered from the erosion of general surgery by the specialties, and from the relatively unfavorable compensation for care of the trauma patient relative to that for performing elective specialty operations.

For these reasons, the conferees recommended that the clinical advisory committee address the issue of identifying a limited number of surgical residency training programs which might be interested in and capable of offering a post residency fellowship training experience in a broad spectrum of surgical skills, particularly those related to the management of trauma and emergency surgical disease, in preparation for potential surgical practice on space station, lunar base, or any remote area on earth.

**DEVELOPMENT OF APPROPRIATE MEDICAL EQUIPMENT**

Modern medicine has become so dependent upon devices for diagnosis and treatment that it is difficult to imagine how medicine could be practiced without arrays of devices. It is equally difficult to imagine how many of these devices could operate in the absence of either unlimited size, weight, electrical power or of gravity. These limitations of imagination may result in failure to recognize the following: (1) Of equipment which will be needed for medical care on space station or lunar base, a significant fraction cannot be selected off-the-shelf, but will need to be specifically designed for these environments. (2) Of equipment which will need to be specifically designed, a lead time of 2-3 years at minimum will be required from conception to realization of flight-rated hardware.

The challenges related to development of a new generation of miniaturized, remotely computer assisted diagnostic imaging

devices, and to development of a new generation of miniaturized, microprocessor controlled, highly versatile bedside clinical laboratory analysis devices, have been presented. Initial attempts to meet the challenges related to establishing a modular operating theater, maintaining a surgical field, and providing suction of biologic fluids with separation of liquid from air in zero-G, will be described in the next part of this report. The fact that such devices may not be needed on space station or lunar base for more than a decade should not deter efforts to proceed with research and development now, both because many problems are certain to take longer to solve than initially anticipated, and because many flight-worthy designs almost certainly will find a much larger market in hospitals and clinics on earth than on space station or lunar base. Because of this last fact, it can be anticipated that R+D efforts related to space station and lunar base are likely to generate another round of medical "spin-offs", extending into the next century, which will overshadow those in microelectronics and microprocessing which grew out of the Apollo decade.

For these reasons, the conferees recommended that the clinical advisory committee include (and receive input from other) clinical device oriented bioengineers, and that this body begin now to develop specifications and project required lead times for the diagnostic and therapeutic equipment which will be needed to deliver the spectrum of clinical care desired for space station and lunar base. As these specs and time frames are agreed upon, selected segments of industry should be challenged to meet these criteria: The clinicians should not be dismayed at the apparent difficulty involved in compacting existing radiographic, laboratory, and surgical equipment; rather they should focus on providing the design engineers with the clearest description of what is needed, and allow the engineers to wrestle with alternative solutions. The big payoff, as first observed, will be the demand by prehospital transport systems, emergency rooms, operating rooms, and special care units all over the world.

#### **DEVELOPMENT OF APPROPRIATE COMPUTER SOFTWARE AND HARDWARE**

Modern medicine is in a transition period as regards a developing dependency upon computerization of storage and recall of data, and of clinical problem solving algorithms. By the time space station or lunar base are operational, most transmission, organization, interpretation, and filing of information in modern hospitals will be accomplished electronically. In addition, much initial and most ongoing medical education, as well as most library reference searching will be accomplished electronically, probably using personal computers linked to regional and national educational and archival centers. Space station and lunar base will need to take advantage of this technology, not only because of constraints of space limiting onboard processing and storage, but also because it will be state-of-the-art.

As has been previously pointed out, during this transition in intensive care units, there have developed wide disparities



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between what clinical data is processed versus what data is useful. In the development of archival, educational, and reference data bank systems, it can be anticipated that similar discrepancies will develop between what data is needed and what is available for recall. Even more distressing, in the computerization of problem solving logic there will be disagreements between the algorithms that are available and the problems which are actually encountered for which a solution is not otherwise obvious. Yet computerized clinical data storage and recall, educational and reference data access, and problem solving and decision making algorithms will be even more vital to high quality clinical care on space station and lunar base than to practice on earth.

For these reasons, the conferees recommended that the clinical advisory committee include (and receive input from other) clinical medical computing bioengineers, and that this body begin now to develop specifications and project lead times for the computing software and hardware which will be needed to support the level of clinical care desired for space station and lunar base. As with the other diagnostic and therapeutic equipment just discussed, the following concepts are important: Computer data management programs that are and likely will be available "off-the-shelf" will not best meet the needs of this system. Appropriate clinical specialty physician input, as regards needs of the system, should be obtained on the front end. Adequate lead time is needed to develop and evaluate the programs and hardware. For industry, a ready market for similar programs exists in medical care facilities all over the world.

A "natural" setting in which to develop such programs will be the special care units of major medical center teaching hospitals which are linked to university departments of medical computing. An obvious setting in which to operationally test the programs will be use by the mission control flight surgeon and specialty consultant network, with initial applications to relatively simple problems whose solutions are otherwise known.

#### **CLINICAL SPECIALTY CONSULTATION RESOURCE NETWORK**

A number of points regarding the use of clinical specialty consultants have been made: Rapid access to a network of specialty expertise will be important not only because of inability to predict and plan in advance for all possible problems, but also because specialty consultation problem solving represents the current standard of clinical practice. Ability of a consultant to provide maximum assistance will require prior and thorough understanding by the consultant of the environment in which the problem must be managed, and access by the consultant to maximum data relative to the problem at hand. In descending order of previously demonstrated value of modalities of data transmission are: person-to-person audio, video, and computer CRT. Since space station and lunar base imply permanent presence in the remote setting, and since it unlikely will be practical to continuously maintain a cadre of specialty consultants at mission

control, then it would appear that effective and efficient access to the consultants can best be established by siting the appropriate communications terminals at the locations in which the consultants regularly practice clinical medicine and bioengineering. The best method of requesting and coordinating input from specialty consultants will be through the mission control flight surgeon. The clinical specialists will function as advisors to the mission control flight surgeon and onboard surgeon; as with other clinical consultation, the latter can accept or reject the advice of the former.

Dr. Trunkey observed that, in general, disaster planning in U.S. cities and hospital systems is, in itself, a disaster. This is because those elements well recognized as being keys to success: communications and assessment/mobilization/deployment of resources, don't work well unless exercised regularly; they can't be exercised regularly unless they are incorporated into daily problem solving; and they usually don't get incorporated. The implication for space station and lunar base is clear: unless a clinical medical specialty consultant network is exercised regularly, it almost certainly will be weaker than desired when needed for a major emergency.

For these reasons, the conferees strongly recommended that the clinical advisory committee help organize an appropriate clinical medical specialty and clinical bioengineering consultation and resource network, and that this body begin now to train itself to respond to a broad spectrum of projected clinical medical problems in space. Sequentially, the following steps appear desirable:

A cadre of initial participants will need to be identified: The conferees are representative of some of the specialists appropriate for the resource network; enough must be identified to include all specialties and provide sufficient depth. Important selection criteria, in addition to recognized expertise, will be the following: willingness of the individual to undergo appropriate initial and recurrent operational medicine training; willingness and ability of the individual and supporting institution to be available to respond to request for consultation; and willingness to participate without individual compensation beyond reimbursement for expenses related to operational medicine training, the opportunity to participate in development of the system, and access to system data for potential publication of results (it would not be inappropriate for sponsoring institutions to receive modest support).

Particularly as regards trauma and emergency surgical problems, selected university surgical faculty may represent an obvious consultant pool for several reasons: Major trauma centers require the round-the-clock physician staffing that occurs almost exclusively in residency training programs affiliated with universities; and university surgical faculty are involved on a regular basis not only in personally assessing and managing surgical disease, but also in explaining to others, in "real

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time," how to accomplish these tasks. From the outset, attention will need to be paid to the "political" implications of consultant selection: it will be important to include enough of the rising "young lions" along with the established "old bulls" in each specialty area. That issue might again best be resolved by looking to selected university departments where the long established professors can both accurately identify and operationally defer to appropriate associates.

The initial specialty consultant pool will need to undergo an initial interval of training in selected aspects of operational medicine. The length of the interval and selection of the aspects might best be determined by NASA flight surgeons, with some advice from the clinical advisory committee. It is anticipated that one of the major benefits of these orientations will be that clinical specialty consultants and flight surgeons (and, at some future date, onboard surgeons) will personally know the individuals with whom they are dealing during subsequent problem solving contacts at long range.

The mission control flight surgeons and initial cadre of specialty consultants should then begin to exercise the consultation network: (1) even just for discussion of relatively simple medical problems for which the solution may already be obvious; (2) even just by telephone before the audio-video-CRT "dish" reception communications hardware is available; (3) and even just for shuttle orbiter flights before space station or lunar base are operational. In addition, the mission simulations, which are frequently conducted for purposes of crew training and evaluating responses to "engineering problems," should also be utilized for training the specialty consultants. This could be accomplished by incorporating simulations of medical problems, and having the mission control flight surgeon activate appropriate components of the specialty consultation network. The experience so gained would be invaluable in exposing bugs in the existing and proposed system, identifying unconceived needs, and perhaps converting some of the unknown unknowns to known unknowns; these insights should more accurately guide further research and organizational efforts.

The clinical advisory committee should encourage early fabrication and installation of the rest of the communication hardware so that it, also, can be exercised and evaluated well in advance of occurrence of a critical problem in space. Its presence will encourage accelerated development and evaluation of computer data management and problem solving algorithms.

The ability to create an easily accessed, smoothly functioning clinical specialty consultation resources network for space station or lunar base could have significant implications as regards practice of medicine on earth. Offering the service to remote or rural communities could represent a major benefit to chronically underserved areas, and could represent a major political feather in NASA's cap. NASA clearly has an opportunity to be in the lead in this pursuit, since NASA will be responsible

for establishing the communications capability, which is so critical.

#### THE MANDATE FOR APPROPRIATE CLINICALLY ORIENTED RESEARCH AND TESTING

It has been repeatedly emphasized that several years lead times are needed for the research, development, and testing of equipment, techniques, and systems needed for an acceptable level of even basic emergency medical care on space station or lunar base. It is anticipated that with permanent presence of about 150 people, on site capability in each clinical medical specialty will be needed. There remain large gaps in our knowledge about physiologic and immunologic responses to illness and injury in zero-G; these include questions about the influence of fluid shifts on an otherwise compromised cardiovascular system, ability of blood to clot satisfactorily, apparent defects in T-cell function, nutritional support of an otherwise catabolic host. Yet with generally healthy astronauts and relatively less healthy budget limits, it has been difficult to generate a very high level of interest in developing capability for clinical medical care in space. Some of the necessary research and testing might be accomplished by sandwiching-in projects on various shuttle flights. However a great deal more could be accomplished on a mission dedicated to clinical medical research.

For these reasons, the conferees strongly recommended that the clinical advisory committee should encourage clinicians to take the initiative in approaching NASA and congress now with suggestions of studies, development of systems, appropriate time frames, and methods of coordination within the clinical medical community. A general goal should be education of key government officials as regards probable clinical medical needs in space. A specific request should be that of dedicating a spacelab mission to a round-the-clock 7 day interval of clinically related medical research, to include pathophysiologic studies as well as testing of clinically related techniques and equipment. Evaluation of a zero-G surgical module, as described in the next part of this report, is representative of technique and equipment testing requiring this unique environment which can be simulated only very imperfectly on earth. In likeness to offers extended to the basic science biology community-at-large in the past, the clinical medical research community should be invited to propose studies which cannot be conducted or cannot be conducted as well without the unique zero-G environment.

For clinical medical research in general and for a dedicated spacelab mission in particular, peer review of proposals would be in order. A group recently established, within whose purview such review might be thought to fall, is the American Institute of Biological Sciences panel on space station, to which Dr. Trunkey is the American College of Surgeons' representative. Dr. Trunkey pointed out that there are at least 2 potential

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difficulties that could be encountered if proposals are triaged exclusively to that group: First, the group contains a single clinician (Dr. Trunkey) who can render an expert opinion regarding value of clinically oriented studies, particularly those related to trauma, emergency surgery, and the pathophysiology of acute illness and injury. Second, we need to be planning and testing now, in the shuttle program, if we are to achieve desired surgical (and other medical) capability on space station or lunar base by the end of the century.

**THE QUESTION OF COST VERSUS VALUE OF CLINICAL MEDICAL CAPABILITY**

The question of apparent value derived for each dollar spent is inevitably raised in justifying each component of NASA's budget. In assessing the potential value of a system for the management of trauma and emergency surgery in space, the following observations can be made: Medical care expenditures currently account for about 10% of the GNP. Medical care benefits have become one of the leading issues annually negotiated between employees and employers. Medical care is expensive, but it is viewed by most of the U.S. and European population as one of the more essential and important issues in their lives. Medical care (intervention after the fact) is of much higher priority to many Americans than health care (prevention before the fact): For example, Americans activity petition and vote against (involuntary) elimination of tobacco, alcohol, firearms, and unsafe automobiles.

These observations in mind, it can be anticipated that before very many people permanently occupy space station or lunar base, there will be a demand for clinical medical care on a parity with that on earth. Delivery of that care will require a significant amount of R+D with significant lead time. While NASA is not and should not be in the business of delivering medical care, it is in the business of R+D which encourages and facilitates the exploration of space. Now is the appropriate time to pay the price for the R+D needed for the clinical medical capability which, in turn, will be necessary for establishing a permanent human presence extraterrestrially. In the course of human affairs, permanent extraterrestrial presence is likely to be of incalculable value.

## **Part 2:**

### **APPARATUS AND TECHNIQUES FOR PERFORMANCE OF SURGERY IN ZERO-G**

#### **INTRODUCTION; STATEMENT OF REQUIREMENTS AND ANTICIPATED PROBLEMS**

In developing capability to provide clinical medical care in space, the acceptable goal is that of parity of quality of care to that available on earth. In achieving that goal, an important early objective will be establishment of the capability to manage trauma and perform emergency surgery in space. In achieving that objective, important components will be planning for the presence of a well trained surgeon, and development of apparatus and techniques appropriate for performance of surgery in zero-G. Arguments supporting the stated goal, objective, and components are presented in detail in Part 1 of the report on System for the Management of Trauma and Emergency Surgery in Space.

In developing apparatus and techniques with which to manage trauma and perform emergency surgery in space, key issues to be addressed will include the availability of personnel, working space, appropriate equipment, the presence of the zero-G environment, and the need for specific personnel to develop facility using specific equipment in that unique environment.

Assuming the presence of a fully trained surgeon, the need for assistance during early space station operations should be adequately met by the ability to pretrain and then reinstruct in real time the typical mentality and personality represented by most astronauts, particularly other physician astronauts or crew members with paramedical training. Probability of success can be enhanced by design of protocols and equipment based on this premise as regards background and training of available assistants.

It is anticipated that during early space station operations, most available working space must be designated multiuse, with minimal dedication to medical purposes. Success therefore will be dependent upon creation of compact modules, capable of temporary functional expansion into multiuse space, carefully integrated from the outset into overall space station design.

It is anticipated that most of the required surgical instruments and support equipment can be obtained "off-the-shelf" in a terrestrial operating room. What will require some thought and experimentation is the development of effective and efficient ways to retain yet permit easy access to the necessary instruments and equipment in the zero-G environment. An obvious first thought, for example, is the use of a magnetic catch surface for an instrument "table." What is not so obvious is the fact that orienting the surface "vertically" or "overhead" will place the instruments in closer proximity to the operating field,

a particular asset if a scrub nurse is not present.

Other available equipment, although of appropriate size and power requirement, can be expected to fail in the zero-G environment. An obvious example is a standard medical suction unit, which must be capable of concurrently aspirating fluids and air. These units depend upon gravity to separate fluid from air in a collection chamber, proximal to the pump, and to prevent a float valve from cutting off suction until the collection chamber is full. One could consider filtering fluids from air proximal to the pump, but blood and protein-rich solutions so quickly occlude typical filters as to preclude continuous operation.

In absence of ability to separate liquids and gases proximal to a suction pump inlet, one of 3 things would happen: If the pump outlet were left inside the space station pressure vessel but without a container attached, aerosolized biologic fluids would be spewed into the room. A "sponge" could be positioned to absorb most of this, but it would be inconvenient to frequently replace it. If the pump outlet were left inside the pressure vessel and a closed container were attached, the pump would have to be left off most of the time or the container would rapidly fill with air so as to either burst or overcome the pump with back pressure. If the pump exhaust outlet were positioned outside the pressure vessel, the pump would have to be left off most of the time or the atmosphere of the room would rapidly be evacuated. In any event, the usual continuous suction capability required for so many medical applications, including surgical suction, would not be available.

Decision to generate a partial gravitational field is an option which could eliminate the zero-G question. This might not require as much circumference, rotational velocity, and energy as one might initially imagine, because only a fraction of a gravitational force, perhaps 0.1 or 0.2 G, might be sufficient. However the mechanism to accomplish this would necessarily increase complexity and cost and decrease reliability and versatility. This latter issue, versatility, is a significant concern in emergency medical systems. It will be desirable to be able to commence and maintain resuscitation, and even surgical procedures, in the widest variety of circumstances and locations in space. Therefore it will be desirable to direct initial attention to a system capable of functioning in zero-G.

Given the decision to operate in zero-G, there appear to be at least 3 problems which will require solutions substantially different from those used in establishing surgical capability in remote (or combat) areas on earth:

1. A mechanism must be created to allow surgeon, patient, anatomic components of interest, and instruments to be reliably positioned and conveniently repositioned relative to each other. Fixing the patient is obvious and retaining instruments has already been mentioned, so this problem reduces to that of allowing the surgeon's body sufficient freedom of movement to

rapidly reposition head, arms, and hands; yet providing sufficient stability to permit precision manipulation of tissues and instruments.

2. A mechanism must be created to allow continuous suction of mixtures of biologic fluids and air, with separation of fluids from the air and collection of the fluids proximal to the suction pump. In order to prevent formation of "blood clouds" over the operating field, this suction-separation capability will probably have to be connected both to a standard sucker tubing for local removal of fluid from the incision, and to a horizontally oriented laminar airflow unit, for more general removal of fluid from the area over the operating field.

3. These mechanisms, to be adequately validated, must be evaluated during the performance of surgical procedures in a zero-G environment.



## **BASES FOR INTENDED SOLUTIONS**

### **RETENTION SYSTEM FOR THE SURGEONS**

Fixation at the forearm would assure control of delicate movements of the fingers and hands, but would prohibit convenient repositioning of shoulder, upper arm, and elbow; most surgeons are taught to use these latter movements so that the hand and instruments remain comfortable extensions of the forearm rather than having to force the wrist and instruments into an awkward angle from which to operate. No fixation, or fixation only at the feet, would allow unlimited ability to reposition the upper body, but the phenomenon of "reaction" of the mid and lower body in response to "action" of the upper body would likely leave the upper body insufficiently stable to facilitate the desired precision of control at the wrist.

A reasonable first compromise appears to be a fixation system which restricts all motion at the feet (unless the feet are voluntarily repositioned), restricts at least up-down and possibly fore-aft motion at the waist, but allows voluntary left-right and possibly fore-aft motion at the waist. The notion that fixation no more cephalad than the waist will suffice is strengthened by experience obtained attempting use of surgical instruments while restrained only by a lap belt during zero-G parabolic arc maneuvers in the NASA KC-135 aircraft. The desire to avoid involuntary left-right movement at the waist suggests that the restraint mechanism should be designed so that translation along that axis can be arrested immediately in zero-G by using minimal voluntary ankle flexion or extension to "friction-lock" a sliding component of a waist belt.

### **MEDICAL SUCTION SYSTEM**

Reasons have already been presented as to why standard medical suction apparatus will fail in zero-G, and why use of filters to separate biologic fluids from air proximal or distal to the suction pump will fail to allow continuous suction. One alternative currently being advocated by a German physician is to simply abandon hope of being able to continuously aspirate biologic fluids, and attempt to contain such fluids in a sealed transparent enclosure applied relatively closely about the patient or anatomic component(s) of interest (Mulke HG: Equipment for surgical interventions and childbirth in weightlessness. 1979; AA 807:1-5; Attachment D). Short of a transparent enclosure might be the interposition of a relatively small transparent rectangular plane between the surgeon's face and the operating field, with room for hands and arms under the window: in effect, a salad bar shield.

There are at least 2 major objections to the transparent shield concept in zero-G: First, blood and other biologic fluids will continue to form "clouds" between the operative field and the shield, and fluids will accumulate on the inside surface of the separator. This will, at minimum, obscure binocular vision,

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important at close range for depth perception. If attempt is made to wipe blood from the inside of the partition, the effect is likely to be similar to using a dry windshield wiper to remove a bug splattered on a windshield of a car: The smear may obscure vision more than the original spot. If clear fluid is squirted on the partition before wiping (windshield washer & wiper on the inside of the salad bar shield) the resulting fluid cloud will drift about (including back into the wound).

The second objection is even more fundamental: While a transparent enclosure with integral gloves may be functional for a relatively predictable procedure such as childbirth, it is unlikely most surgeons will accept that degree of isolation from a patient when embarking upon a less predictable emergency operation which could require much greater access and mobility in order to safely perform. If the alternatives are a messy room versus impaired exposure, the surgeon's choice is likely to be a messy room.

The goal, clearly, is standard access to the patient and anatomic components of interest, with relatively standard control of free fluids by an aspiration apparatus which can provide continuous suction, collect the aspirated fluids, and return the aspirated air to the room. Accomplishing the latter requires application of a force which can distinguish and separate liquid from gas. Creating local artificial gravity to take advantage of mass difference between the 2 media appears more straight forward, reliable, and generally applicable than alternatives such as attempting to alter the liquid to respond to electric or magnetic forces.

#### TESTING THE APPARATUS AND TECHNIQUES

Short of a flight on the shuttle, there appear to be at least 3 environments in which apparatus and techniques designed for surgery in zero-G might be tested: in a standard laboratory on earth, underwater, and during parabolic arc maneuvers in an airplane.

Practice and testing obviously should be accomplished in a standard laboratory before removal to a more unusual environment. Probable function of certain devices in zero-G might also be verified, for the most part, in the standard laboratory by operating them in an inverted orientation relative to that customary in one-G. For example, relative to its inlet and outlet, the function of a centrifugal air-fluid separator would be assisted by gravity when "upright," relatively uninfluenced by gravity when oriented 90 degrees to "upright," and thwarted somewhat by gravity when "upside down." If the device will work "upside down" in one-G, then, at least as far as the separation function is concerned, it should work as well or better in any orientation in zero-G.

Suggestion has been received from outside NASA to study surgical techniques underwater (NASA JSC Memo SD24/83-M-80 of 5/17/83).

Water would appear to offer only one advantage over the standard laboratory environment: that is the effect of neutral buoyancy. Neutral buoyancy, in a large pool on earth, has been useful in preflight practice of certain EVA activities because the objects to be manipulated in zero-G were of relatively large weight on earth. When the objects to be manipulated in zero-G are of relatively light weight on earth (as is the case with surgical instruments and anatomic components of interest), then the disadvantages of practicing underwater are several and severe:

1. While neutral buoyancy might be of some aid in evaluation of a restraint system for the surgeon, the associated increase in viscosity of the media in which the surgeon must move can be expected to generate sensations no more accurate, relative to zero-G in air, than those experienced in one-G in air. That is, the manual coordination "relearning curve" going from water to zero-G would be no better than going from the operating room to zero-G.

2. The management of free biologic fluids in zero-G appears to be the most significant surgical apparatus problem requiring "novel" solution. It is specifically the need to continuously separate fluid from air which is the challenge; clearly this cannot be simulated in an all liquid media.

3. While free blood is likely to "cloud" underwater, as in zero-G, and while suction tubing attached to a fluid pump could be manipulated to selectively aspirate the blood, it is less probable that small animal surgery will be done in a swimming pool than in an airplane. Ultimately, small animal surgery will be required to validate apparatus and techniques.

The only practical means currently available with which to experience "real" zero-G, short of a shuttle flight, is parabolic arc maneuvering in the NASA KC-135 aircraft. While a maximum of only 30 seconds of zero-G can be generated per arc, up to 40 arcs can be generated per flight. Many surgical procedures can be viewed as constructed of a linked series of "sub-procedures," and satisfactory completion of many of these procedures is not precluded by a series of "stop action" pauses between the sub-procedures. To the extent this fractionation is valid, surgical procedures of up to 20 minutes "usual" duration can be performed in zero-G during each flight in the KC-135 aircraft - provided an apparatus is available which is appropriate both for performing surgical procedures and for flying in the KC-135 aircraft. (20 minutes is more than sufficient time in which to perform most "common" surgical procedures in small animals.)

Despite its imperfections, simulation in the KC-135 appears to offer the best opportunity to obtain early evaluation of apparatus and techniques for performing surgery in zero-G. Therefore a module of appropriate size for small animal surgery has been designed and constructed specifically to function in the NASA KC-135 aircraft.

# ZERO GRAVITY SMALL ANIMAL SURGICAL MODULE

March 1983 April 1983

Scale 1/8" = 1"

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Caption

MODULAR  
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Support Members  
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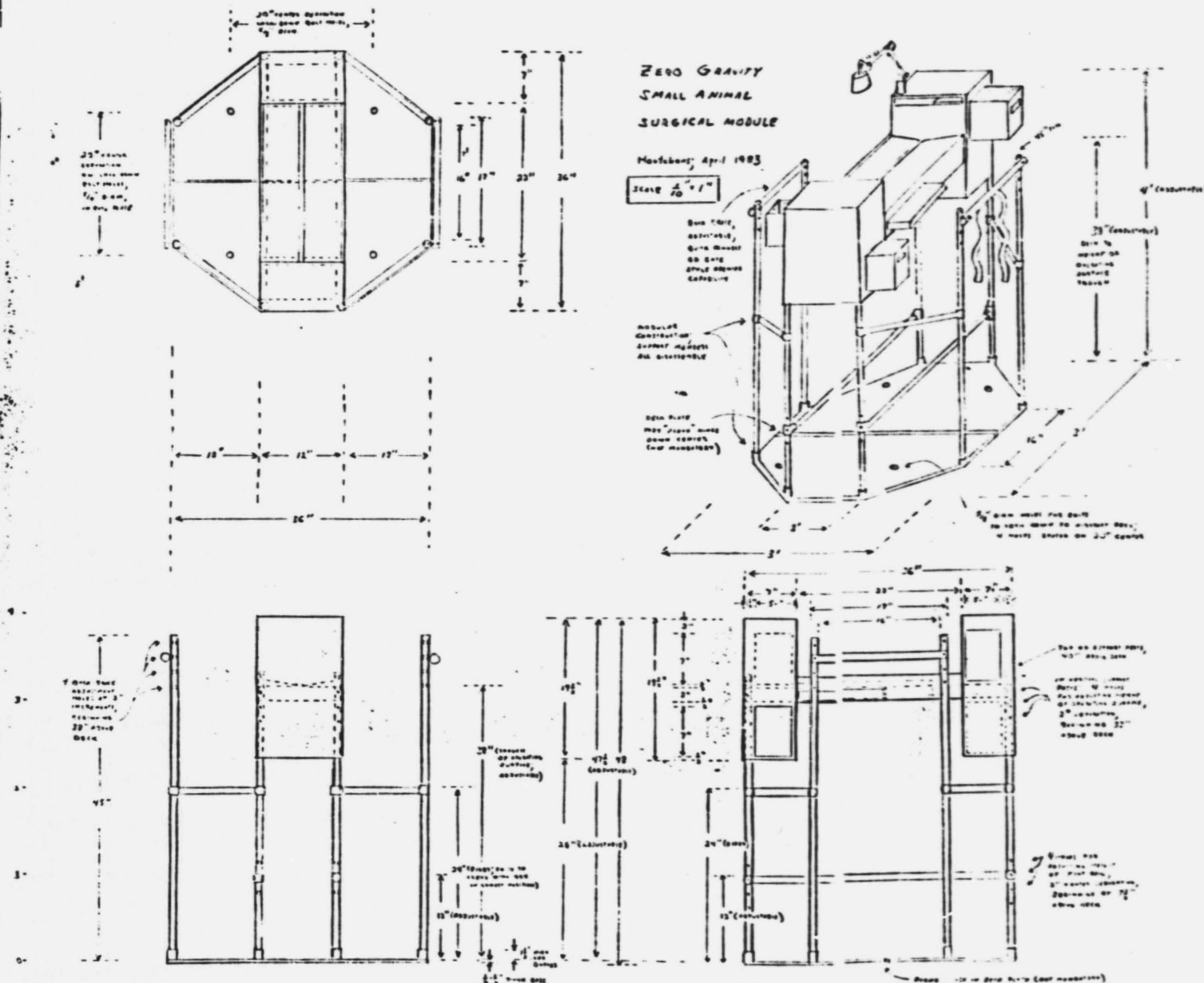
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FIGURE 1

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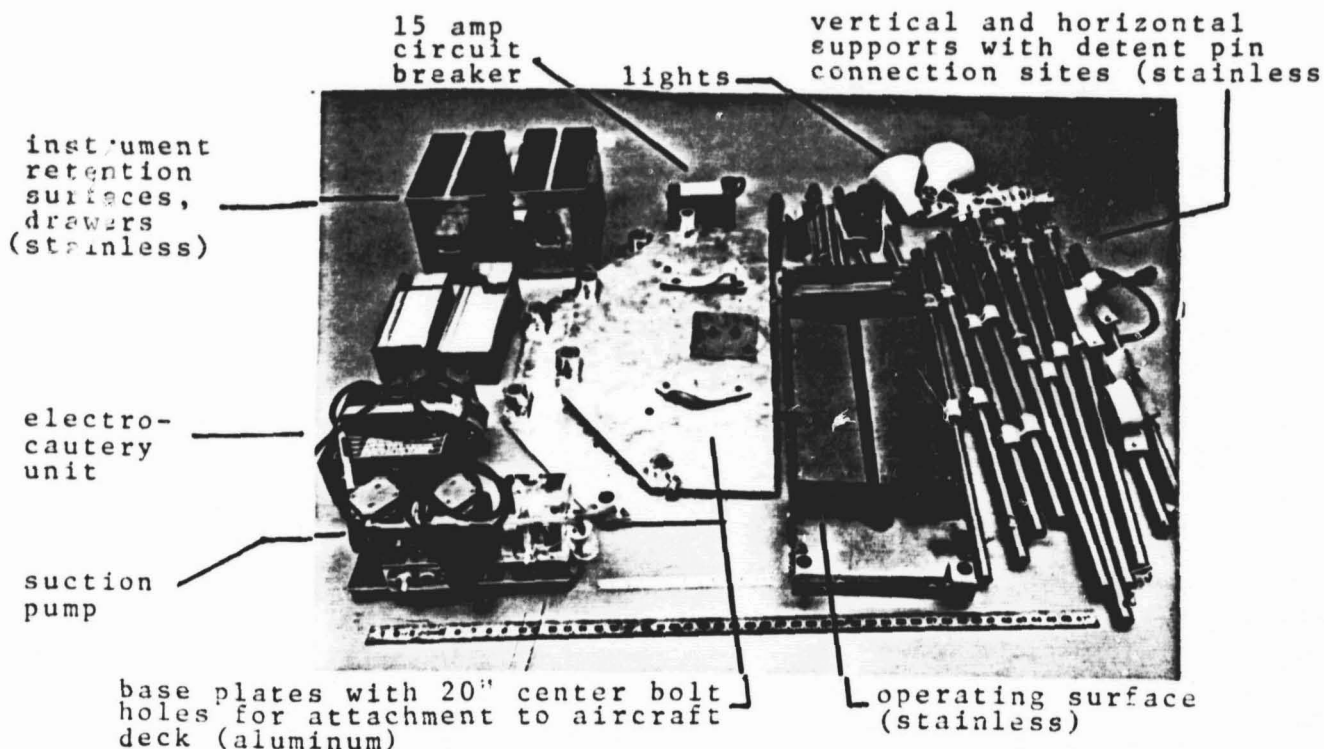


## Size Constraints, Modularity

The intended use of the module suggests it should occupy minimum space in the KC-135, yet be of sufficient width to accommodate surfaces for instrument retention plus space for a small animal, be of sufficient depth to accommodate restraint systems for 2 surgeons, one on each side of the "table," and be of sufficient (and adjustable) height to place the surgical field at about waist level, as is customary on earth. Appropriate minimum width, length, and height to accomplish this turn out to be about 3 feet each; minimum floor surface is occupied if the base is approximately octagonal. Figure 1 indicates the overall dimensions and plans.

Intention to seek opportunities to fly in a "space available" status suggests need to be able to independently and on short notice load the module aboard and unload the module from the aircraft. Construction to FAA standards of structural strength (ability to withstand 9Gs) is inappropriate; thus it must be possible inflight to rapidly assemble and disassemble the "superstructure" of the module during the 20 minute interval of cruise to and from the maneuver area. Therefore the module has been constructed in a sub-modular fashion to facilitate quick connect and disconnect (Figure 2).

Figure 2: Zero-G surgical module, disassembled



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The entire unit can be contained within 2 duffle bags and 2 parachute bags (Figure 3), and can be carried (with some difficulty) by a single person (Figure 4).

Figure 3: Zero-G surgical module, packed for transport

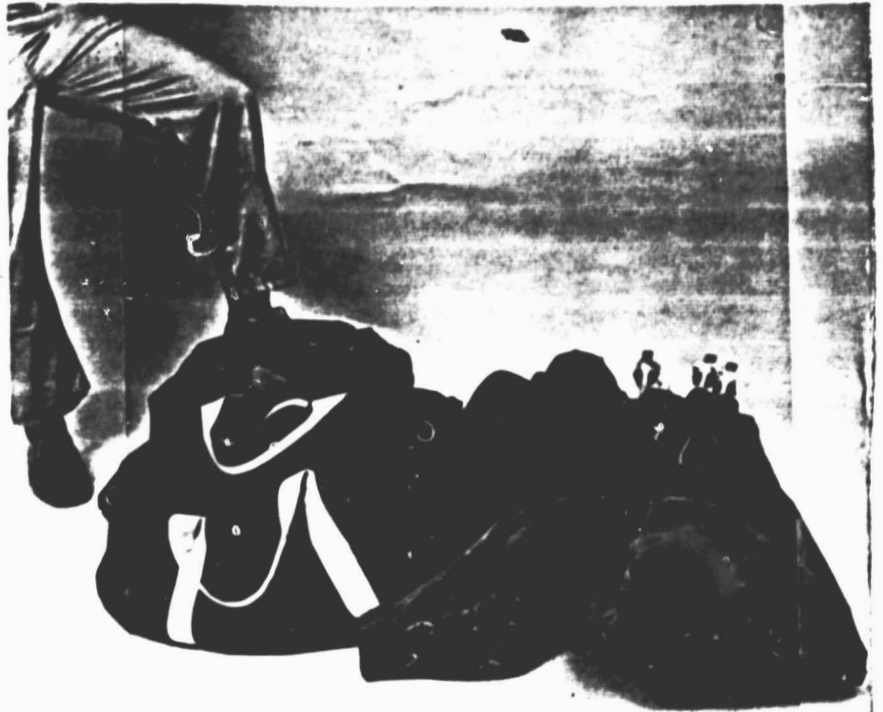


Figure 4: Zero-G surgical module, carried by surgeon



### Assembly

Detent pin connections and quick connect screws permit rapid assembly of the module (Figures 5-8).

Figure 5: Zero-G surgical module, assembled

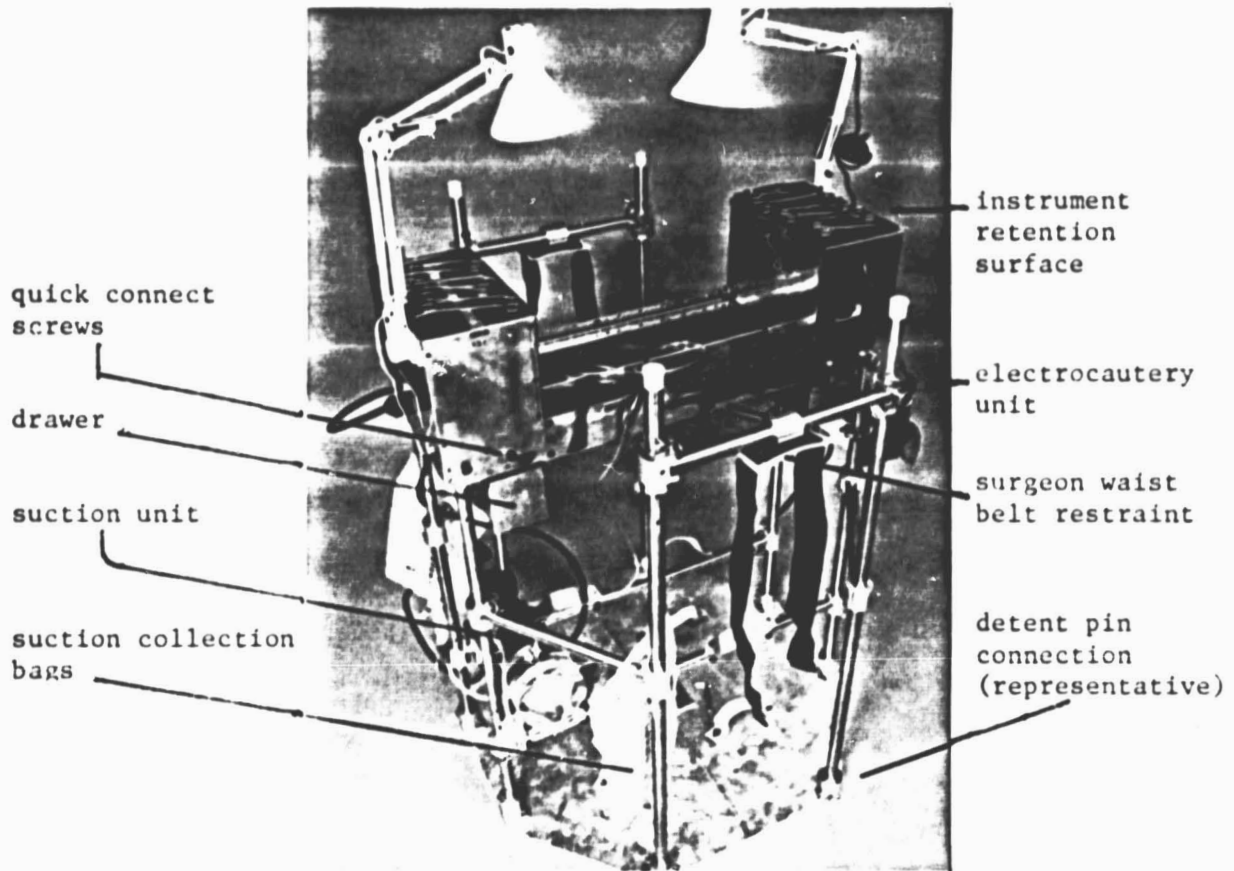


Figure 6: Zero-G surgical module, assembled

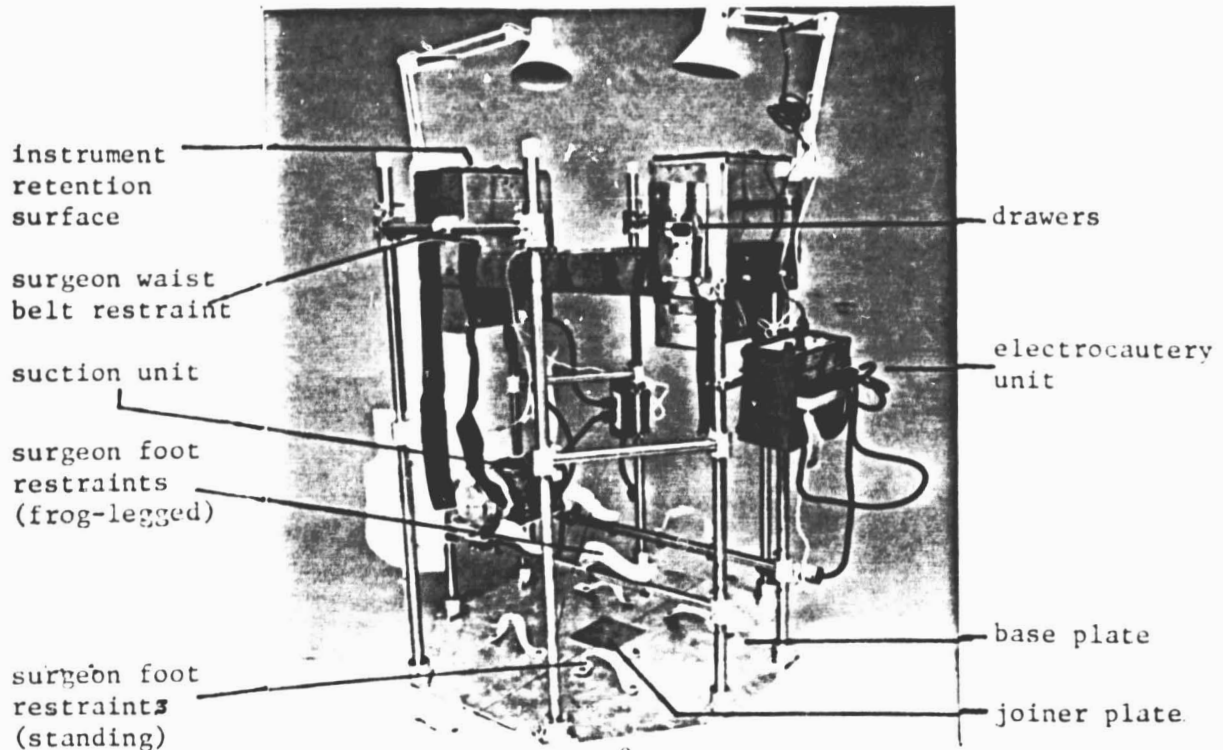


Figure 7: Zero-G surgical module, assembled

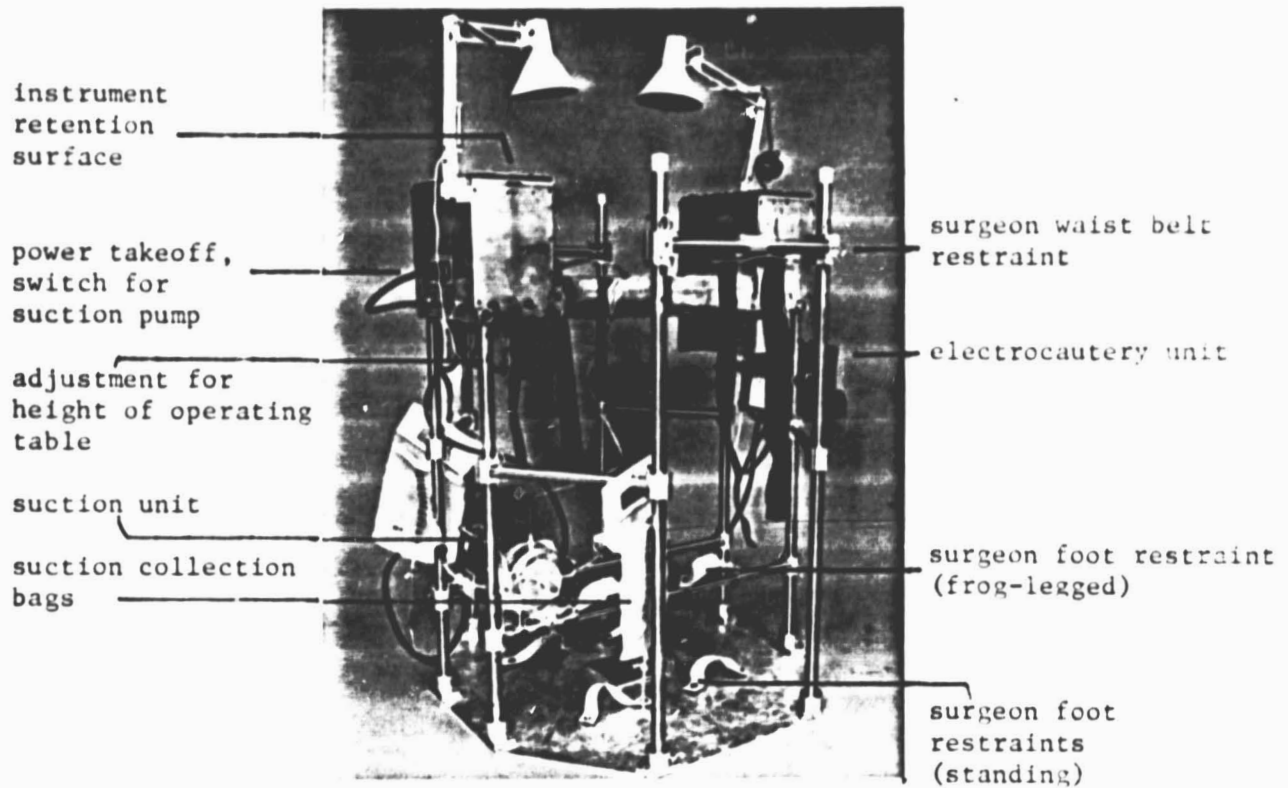
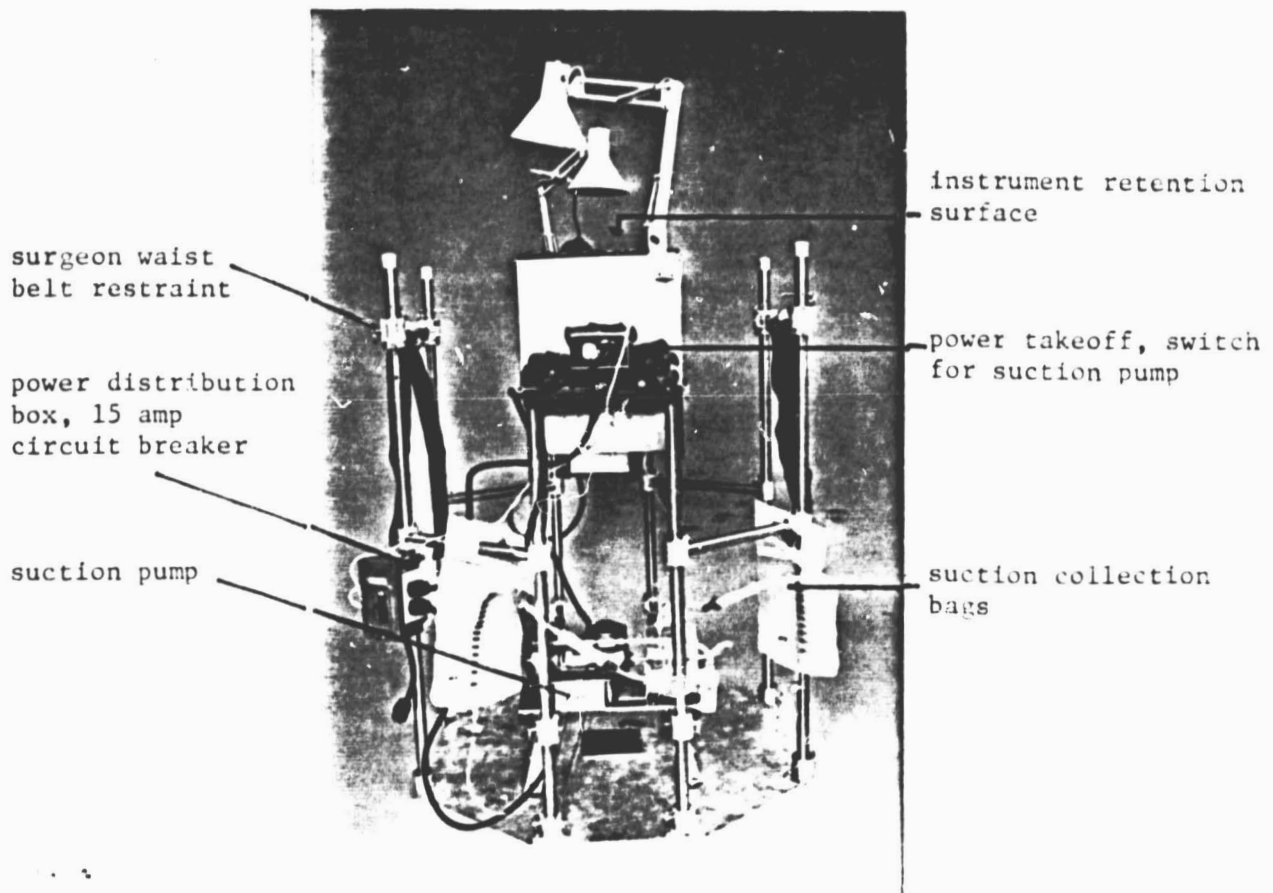


Figure 8: Zero-G surgical module, assembled

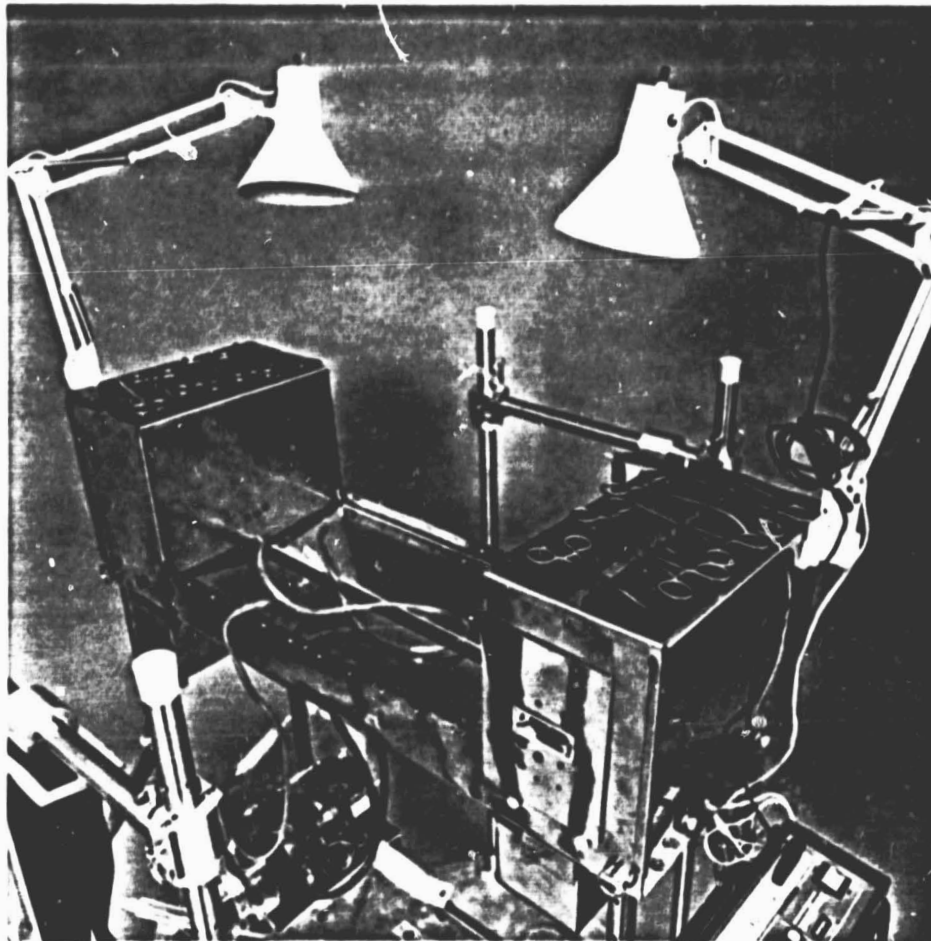




### Surgical Apparatus

The 2 instrument retention surfaces each consist of 2 parallel flexible magnetic strips. The strips consist of iron particles vulcanized in rubber and subsequently magnetized. The width of the strips provides sufficient contact for adequate retention; the groove between the strips allows easy "plucking" of instruments. The variable directional lights are attached lateral to the instrument retention surfaces, creating no obstruction to instrument access and return (Figure 9).

Figure 9: Instrument retention surfaces and light mounts



The electrocautery unit is attached, control panel "up," just lateral to one of the instrument retention surfaces, within easy reach of either surgeon (Figures 10, 11).

Figure 10: Electrocautery unit relative to instrument retention surface

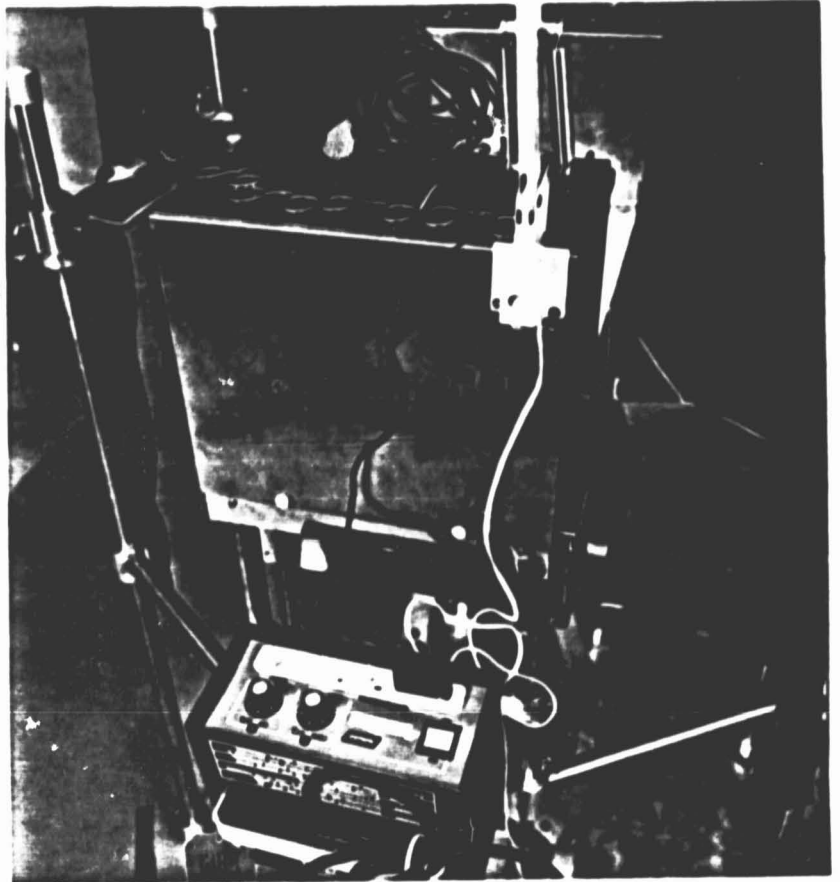
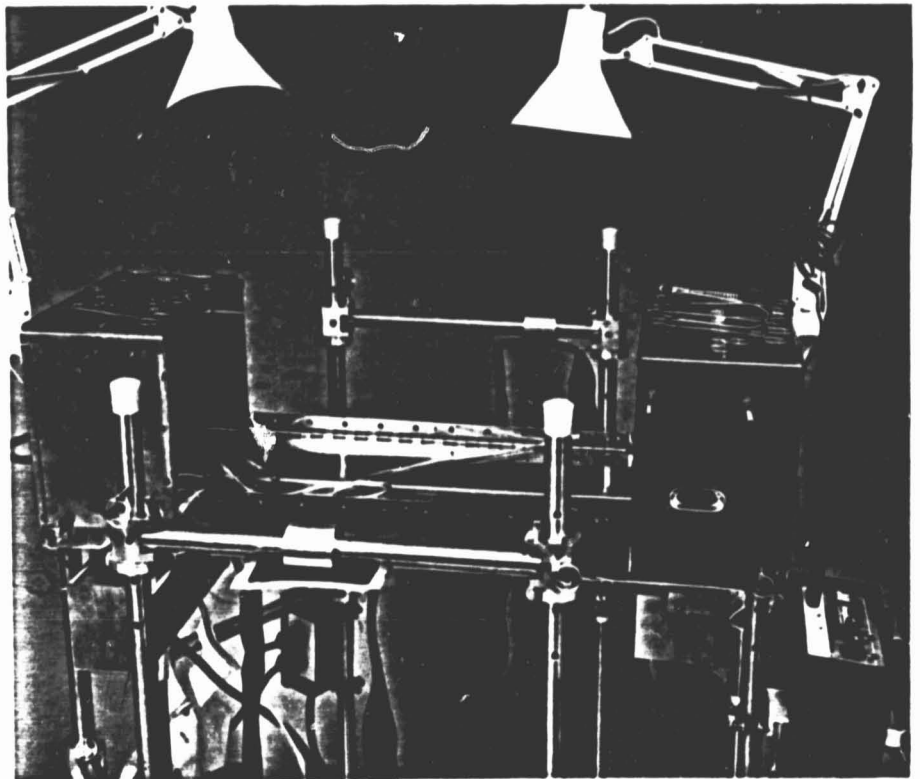
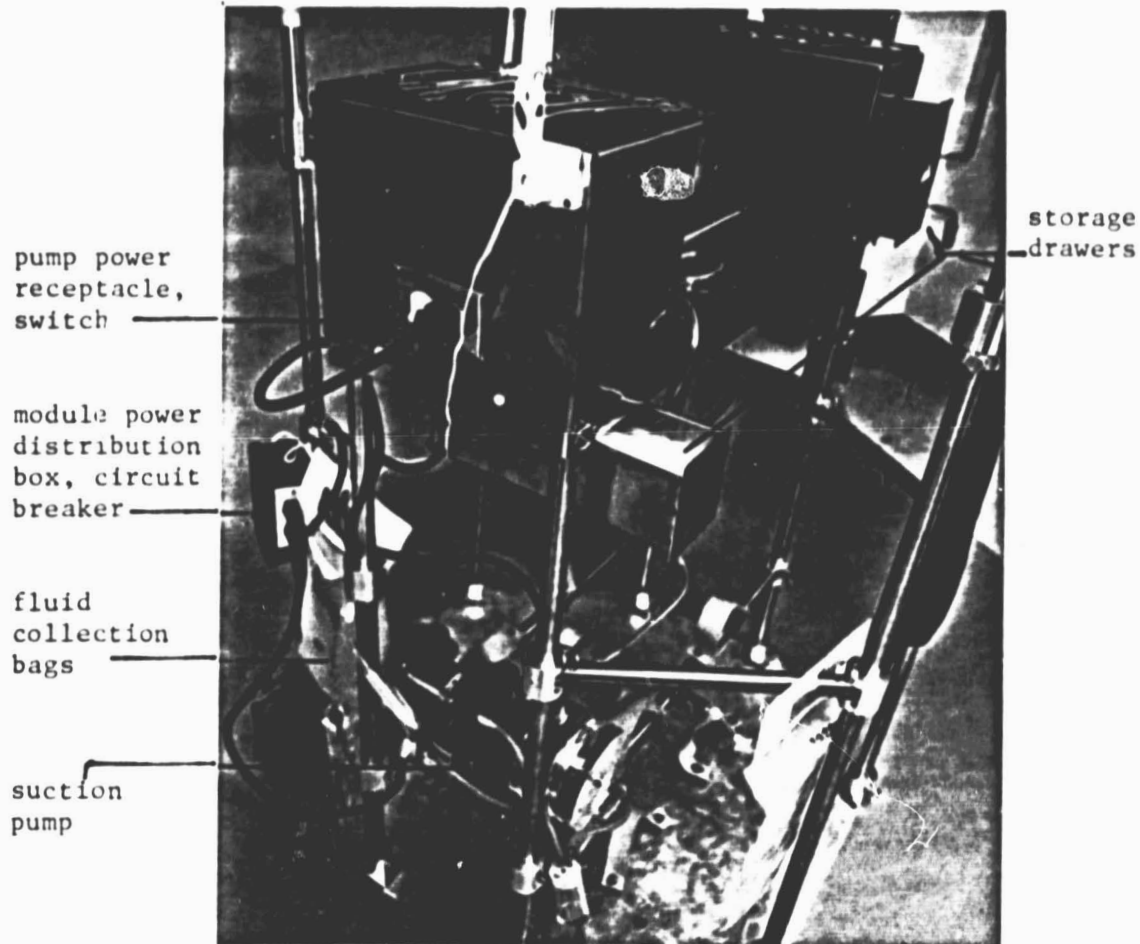


Figure 11: Electrocautery unit relative to operating surface



The suction pump is attached to "horizontal" support bars under the table. Fluid collection sacks are attached to other support bars near each end of the pump unit. Pump power is derived through an on-off switch unit lateral to an instrument retention surface and within easy reach of either surgeon. At each surgeon's right side is a large "top" drawer; at each surgeon's left hand is a small "bottom" drawer (Figure 12).

Figure 12: Suction pump, storage drawers

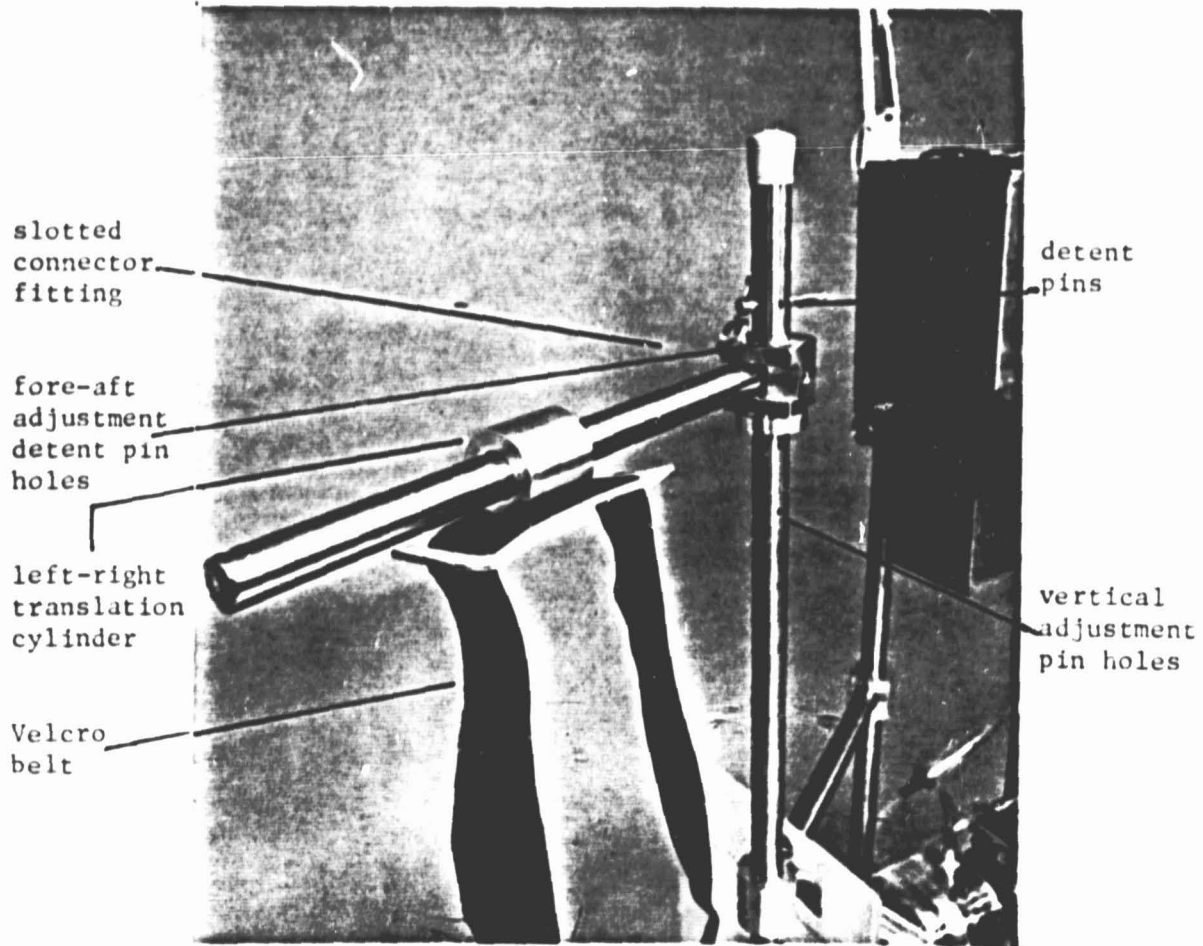


Not shown is an intravenous infusion pump, which attaches to any of the "vertical" supports.

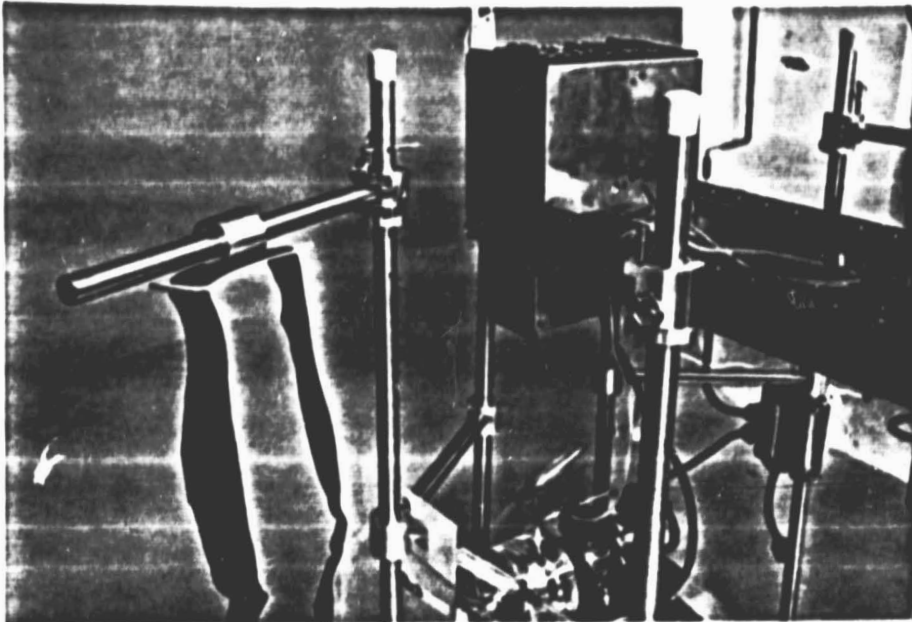
### Surgeon Restraint System

A Velcro fastener waist belt is attached to a hollow aluminum cylinder, which, in turn, fits over a "horizontal" stainless steel tube so as to allow lateral translation. Each end of the horizontal tube fits in a slotted connector fitting, which, in turn, fits over a vertical support tube. Vertical motion on the vertical support tube is prevented by a detent pin; 4 pin positions are available at 2 inch intervals to permit adjustment of height of the waist belt bar. Motion of the waist belt bar to and from the operating table is prevented by another detent pin; 3 positions are available at one inch intervals to permit adjustment of closeness to the operating surface. A platform with set screw can be positioned immediately "under" the slotted connector fitting and the (horizontal) detent pins removed at one end of the waist belt bar. Then, with the other end free, the waist belt bar will swing open like a gate to facilitate easy entry in one-G (Figures 13, 14). (Note: In zero-G, it is just as easy to "float in over the top.")

Figure 13: Surgeon waist restraint belt

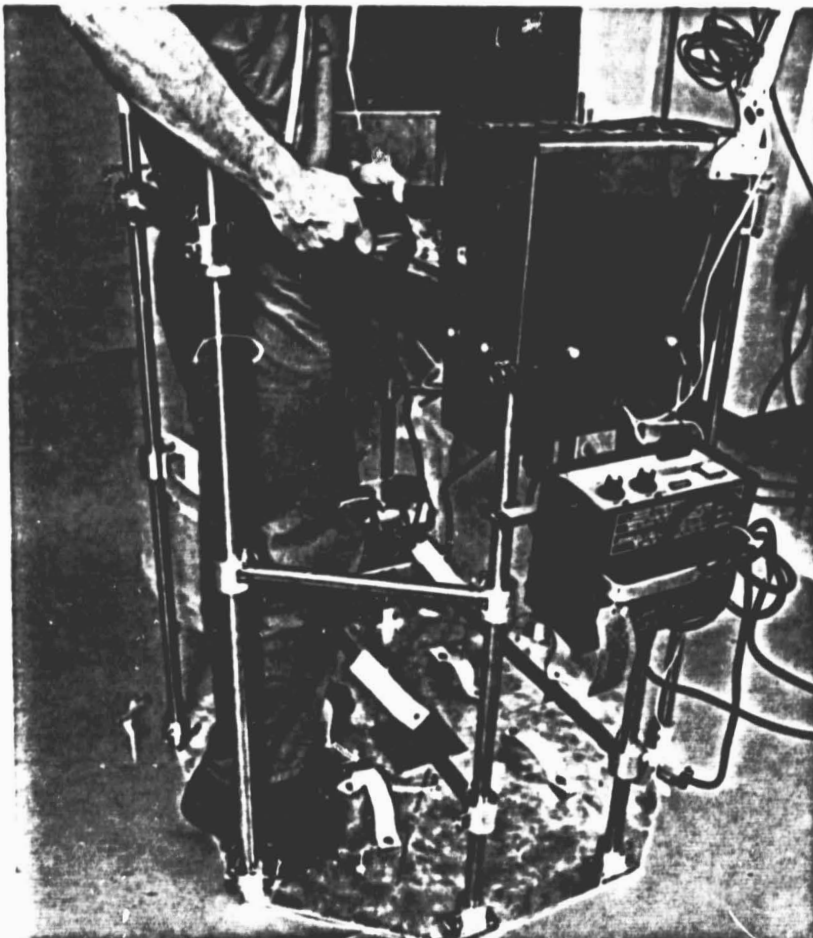


-Figure 14: Surgeon waist restraint belt "gate," open



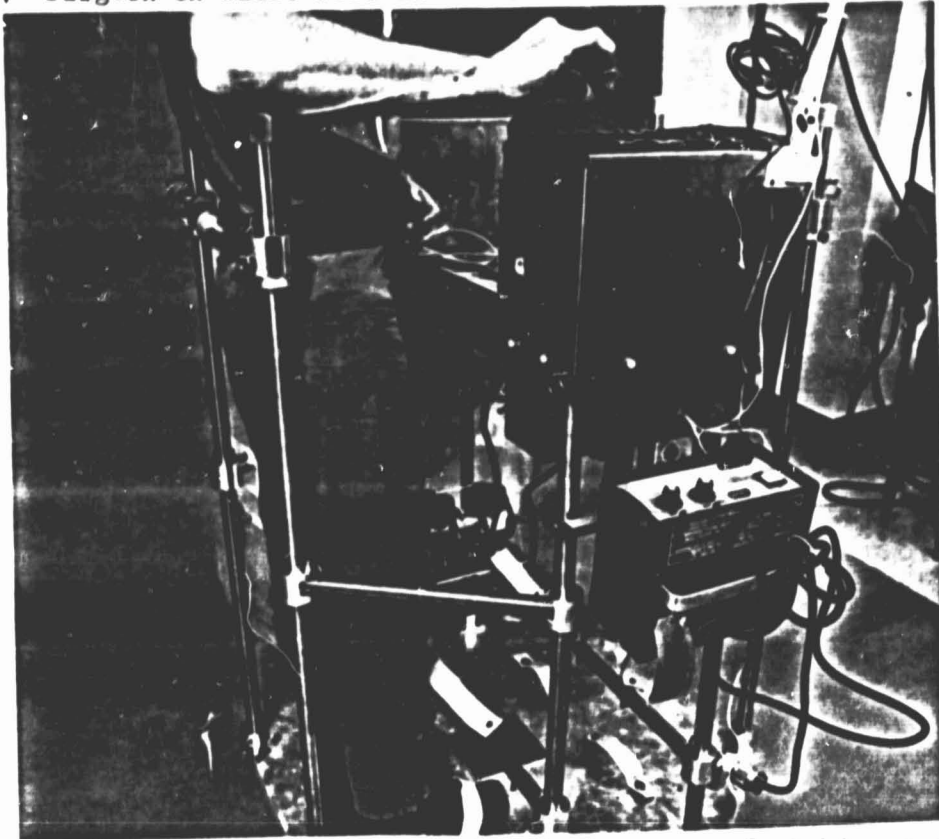
- \* With the gate closed, detent pins inserted, and the surgeon in position, the feet can be inserted into the foot restraints and the Velcro belt attached (Figures 15, 16).

Figure 15: Surgeon stepping into waist belt and foot restraints



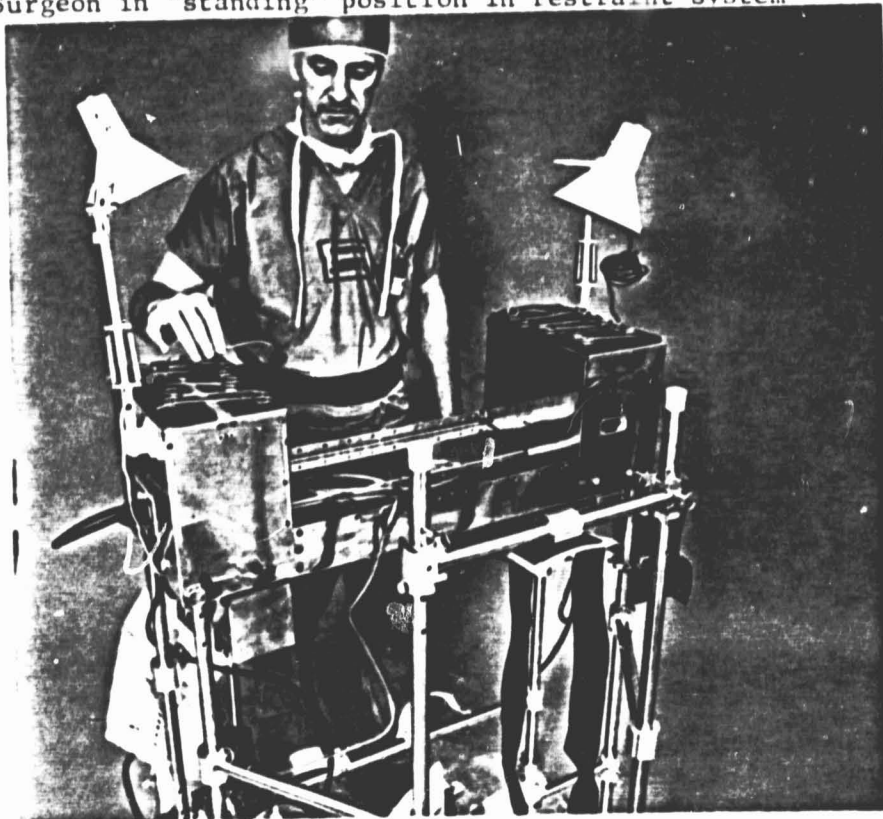
2" interval  
bolt holes  
for fore-  
aft adjustment  
of foot  
restraints

Figure 16: Surgeon in wa-st belt and foot restraints



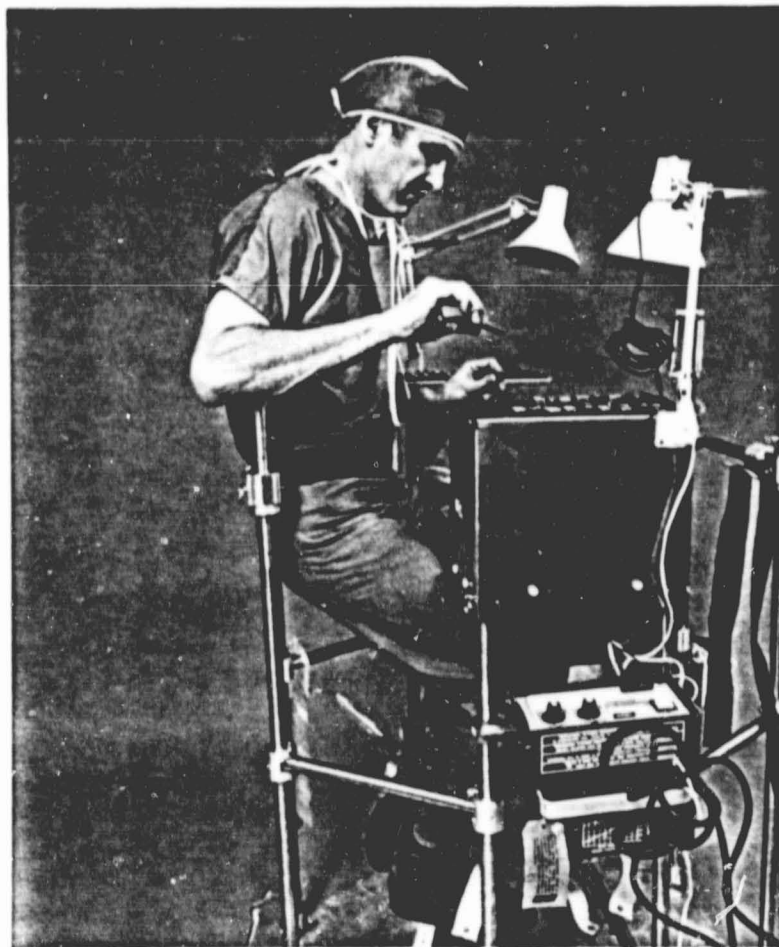
It is anticipated that most surgeons will feel more comfortable operating in the customary "standing" position, even in zero-G (Figure 17). This position also offers the best ankle flexion (heel-toe) control as regards ability to apply pressure at feet and waist to increase stabilization of the upper body.

Figure 17: Surgeon in "standing" position in restraint system



On the other hand, in the absence of conscious muscular effort, the position more "naturally" assumed by the body in zero-G is slightly "frog-legged." Therefore, to test ability to operate in that position, foot restraints have been provided on the "horizontal" support tubes which cross "under" the operating table on each side. The foot restraints can be adjusted laterally on the tubing; the tubing can be adjusted in distance from the base plate at 2 inch intervals by repositioning detent pins in slotted connectors (Figure 18).

Figure 18: Surgeon in "frog-legged" position in restraint system





## **ZERO-G SUCTION UNIT**

### **Background**

To appreciate the novel features of the new system, it is helpful to review certain features characteristic of conventional suction systems for clinical medical management of biologic fluids. These are as follows:

1. The system must be able to aspirate both air and fluid, with relative volumes of air usually exceeding those of liquids.

2. Total volumes of liquids aspirated are usually relatively low.

3. Development of relatively high negative pressures is usually more important than relatively high flow volumes.

4. It is often desirable to be able to develop these relatively high negative pressures relatively quickly.

5. While the system is capable of sucking either air or fluid or both, the pump itself is designed to aspirate primarily air.

6. Pre-pump separation of these media is usually accomplished in a "drop chamber," by gravity.

7. The separation drop chamber is usually also the fluid collection chamber.

8. To empty or change the collection chamber, which is in series with the negative pressure line, suction must be temporarily discontinued, an annoying interruption at times (particularly in the operating room during surgery).

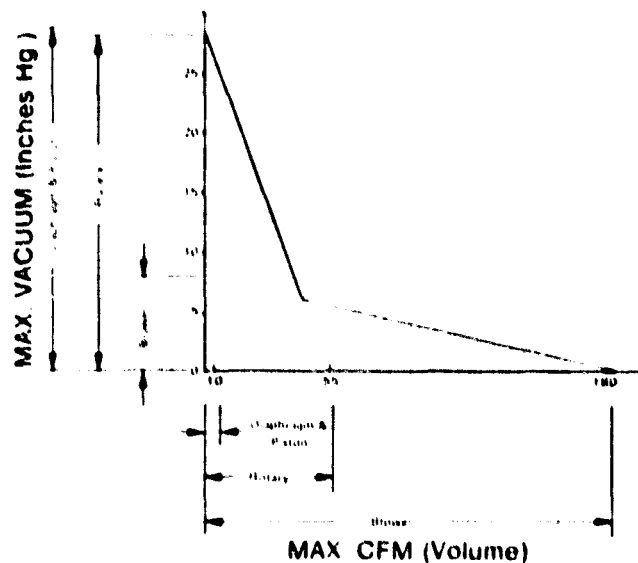
9. To decrease frequency of need to empty or change the collection chamber, this chamber is usually relatively large (1-2 liters).

10. This large collection chamber, in series with the negative pressure line, must necessarily be evacuated in transitioning from an open (sucker tip exposed to air) to closed (sucker tip immersed in fluid) mode of operation.

11. For pumps which do not rapidly exhaust large volumes of air, the large collection chamber therefore introduces a significant delay in developing maximum negative pressure at the sucker tip.



12. The pressure versus flow relationships of most commercially available pumps are such that ability to develop relative high negative pressure (usually desirable for medical applications) is achieved at the expense of rapid flow, as indicated in the following representative plot:



For the foregoing reasons, most current medical suction systems suffer from presence of collection systems which are smaller than optimum from the standpoint of frequency of need to change them, and larger than optimum from the standpoint of delay involved in developing negative pressure during transition from aspiration of air (open) to fluids (closed). In addition, for reasons already discussed, they will fail to function even marginally satisfactorily on a continuous basis in zero-G.

For all these reasons, there has been constructed, for use on the zero-G surgical module, a (previously conceived) Fluid Air Suction Technique for Separation of Liquid INdependent of Gravity (FAST SLING) unit. The device is intended to allow suction of fluids, gases, and mixtures thereof, in clinical and laboratory settings, with pre-pump separation and collection of liquids being accomplished independent of an ambient gravitational force field and use of a "drop" chamber. In the zero gravity environment of a permanent space station, this capability will be essential in order to perform suction and collection of biologic fluids with neither loss nor contamination of ambient station atmosphere. In zero-G or on earth in a continuous one-G environment, the FAST SLING device will allow both immediate build-up of negative pressure and use of a large volume collection system, features desired but not achieved with conventional biologic fluid aspiration systems.

## Construction and Function

In the FAST SLING unit, separation of fluid and air is accomplished by centrifugal force in a small (4" diameter 1" long) rotating cylindrical chamber, rather than by gravity in a large stationary rigid chamber. Rotational force is obtained by "quick connect" coupling of the separation chamber shaft of the FAST SLING unit to the shaft of a commercially available (air) suction pump (Figures 19, 20). The resulting suction unit is about 15" x 6" x 6" and weighs about 15 pounds.

Figure 19: Suction pump disconnected from the assembled FAST SLING separation chamber

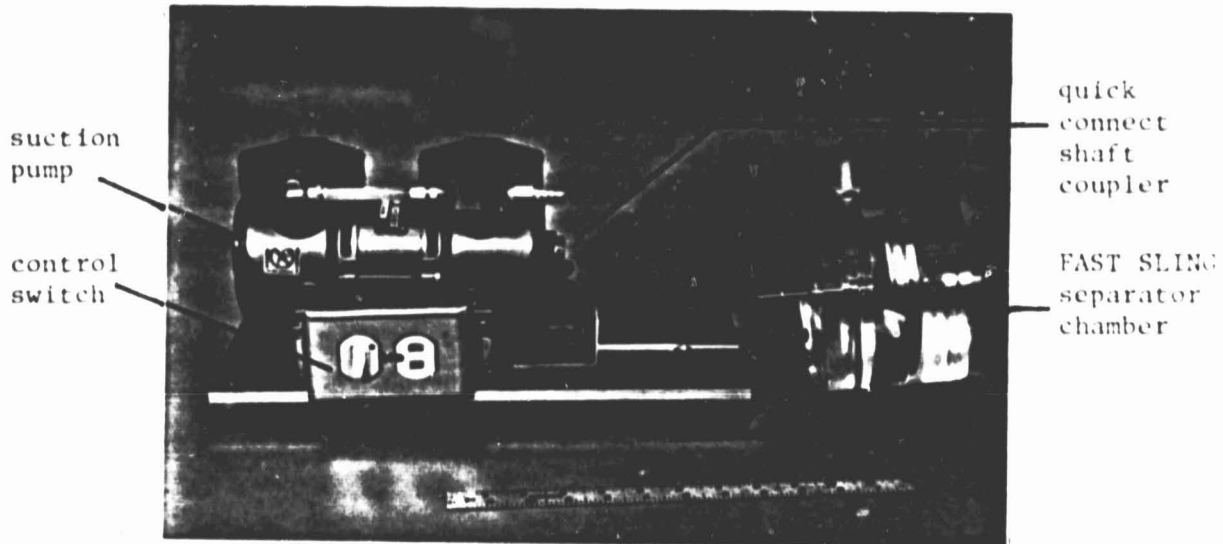
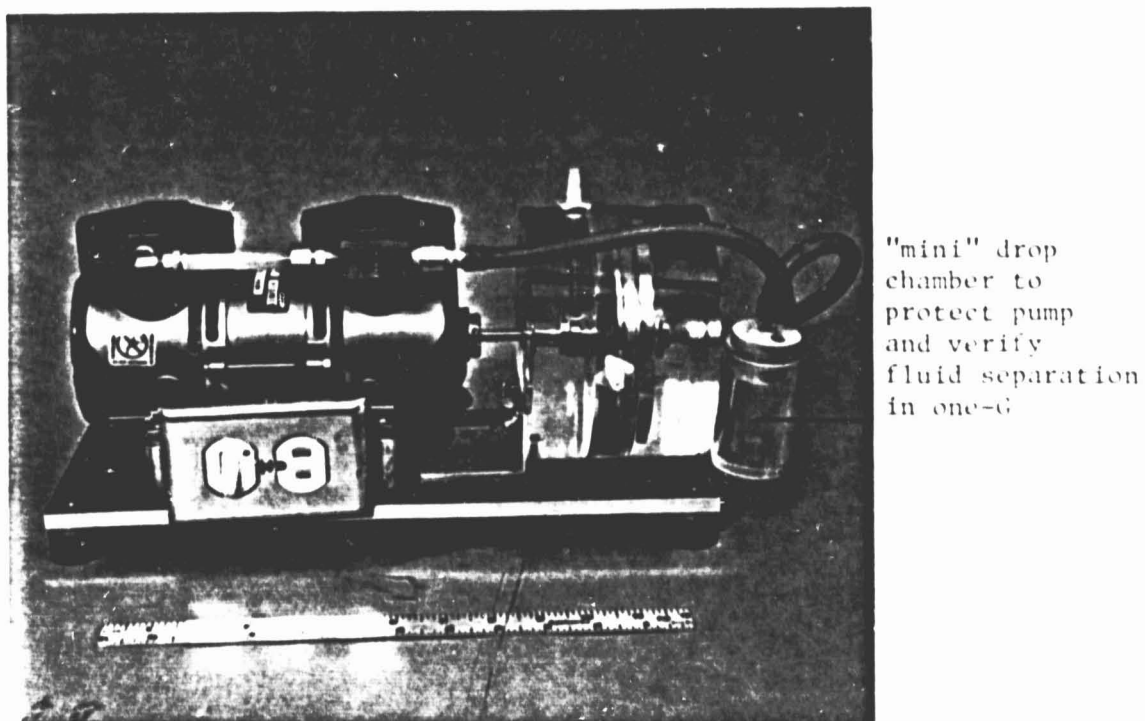


Figure 20: Suction unit, assembled, without fluid collection sacks attached



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The 1700 RPM provided by this pump creates more than adequate rotational velocity within the chamber to achieve fluid-air separation. In fact, testing on a variable RPM lathe suggests that the device is relatively insensitive to RPM decrease to as low as 300 as long as the airfoil of the separator chamber propeller (to be described) is oriented correctly.

Fluid is collected into 2 soft plastic bags of almost any size desired, attached via stationary exit valves at the perimeter of the rotating chamber, rather than into a single large rigid chamber in series with the negative pressure line. The combination of centrifugal separator, linked by one-way valves to stationary collection bags which may be emptied or changed, is novel. (Figure 19).

Figure 19: Suction unit linked by one-way valves to 3 liter plastic collection bags



one-way  
valves

3 liter  
bags

Because the collection bags are collapsible (soft) and joined to the rotating chamber by one-way valves, only the rotating chamber need be evacuated of air in transitioning from open (low pressure) to closed (high pressure) suctioning. Therefore, because the air volume of the rotating chamber is relatively small (about 80cc), a "standard" low volume pump may be used, yet high negative pressure may be achieved rapidly in transitioning from an open (to air) to closed (under fluid) mode of operation. In addition, collection bags of arbitrarily large size may be used, thereby reducing frequency of need for emptying or changing the receptacles, but without introducing delay in development of maximum negative pressures. And, because the collection bags are not in series with the negative pressure line, they may be emptied or changed without interrupting the suctioning process.

The fluid separation chamber housing is divided into a "front" face, containing the aspirate entrance and fluid exit ports, and a "back" face, containing the air exit (to pump) port, between which the centrifugal separation chamber can rotate (Figures 22, 23). The rotating chamber has an open "rim" to allow fluid to reach the exit ports at the periphery.

Figure 22: Fluid-air separator construction

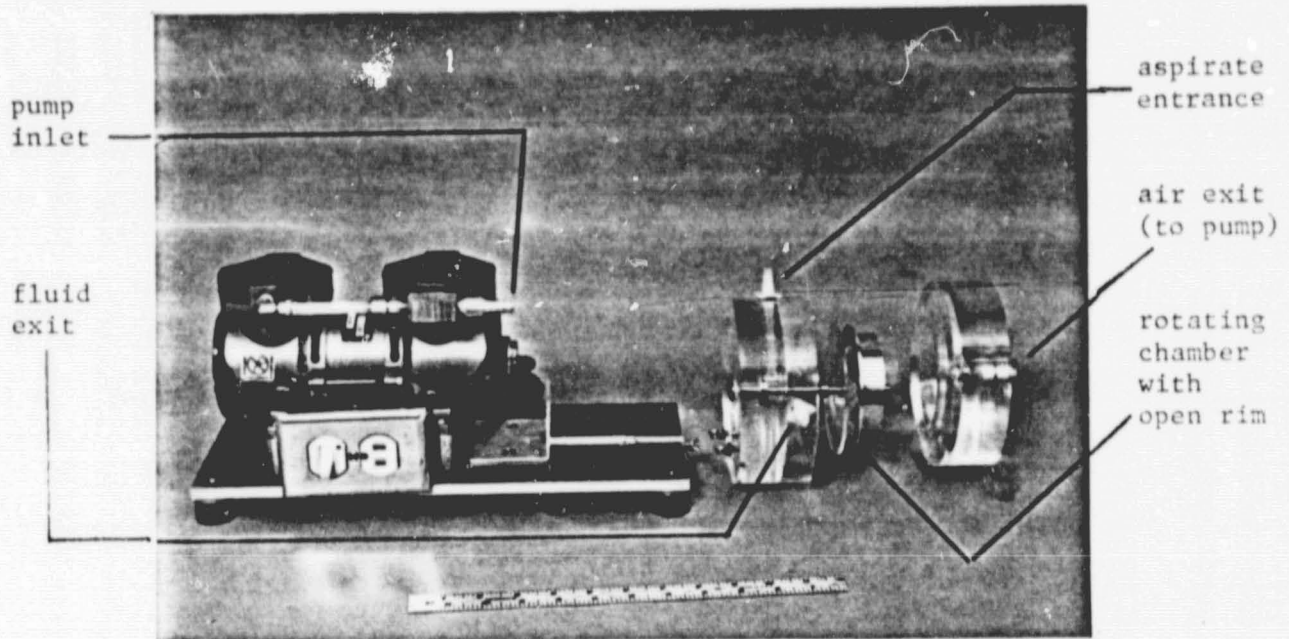
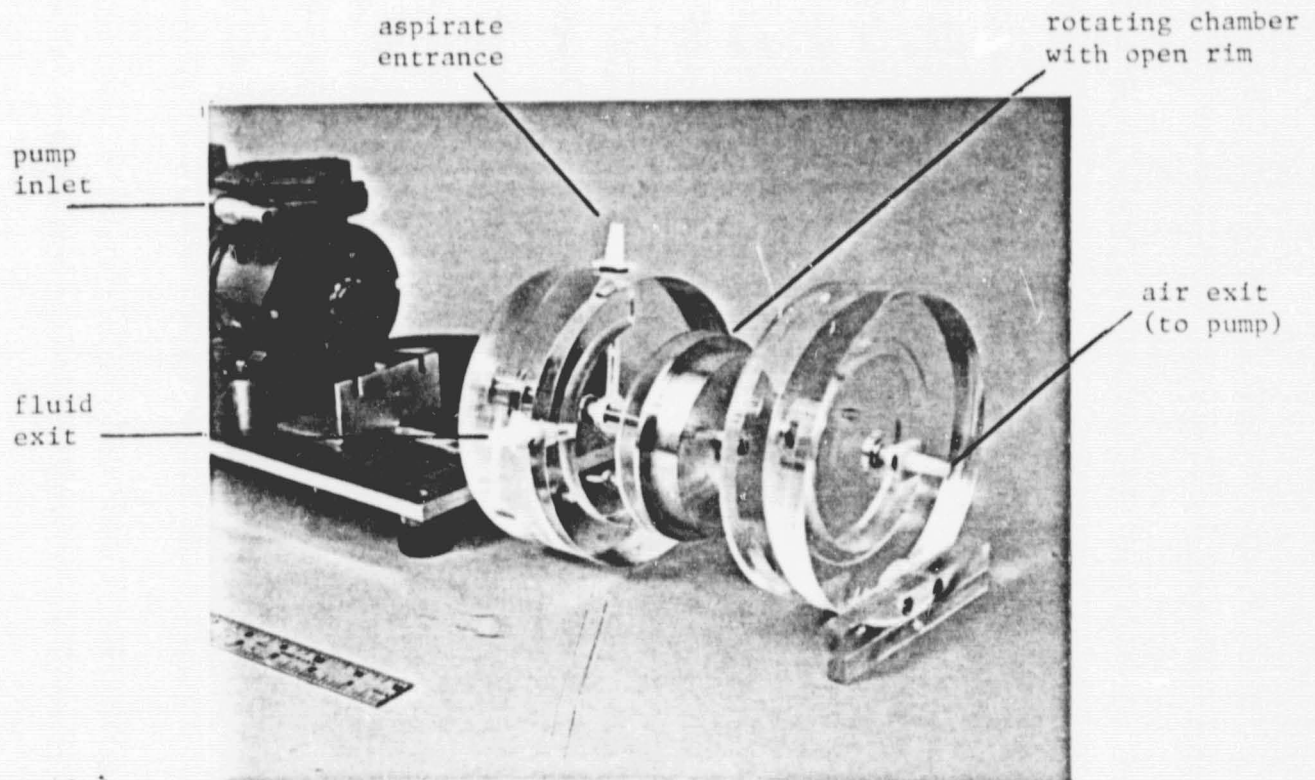


Figure 23: Fluid-air separator construction



The rotating chamber disassembles into a thin disk, against which fluid is thrown by a propeller, and a back housing, against which impacts any fluid which might find its way around the propeller. Fluid enters the rotating chamber through holes in the flanged hub of the disk; air exits the chamber through a hollow shaft at the hub of the back housing (Figures 24-26).

Figure 24: Partial disassembly of rotating chamber

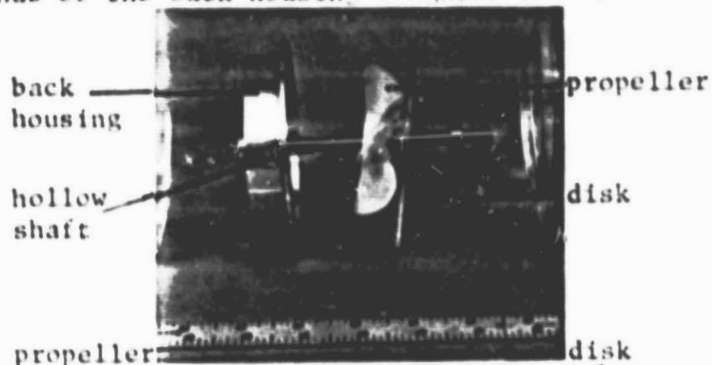


Figure 25: Partial disassembly of rotating chamber

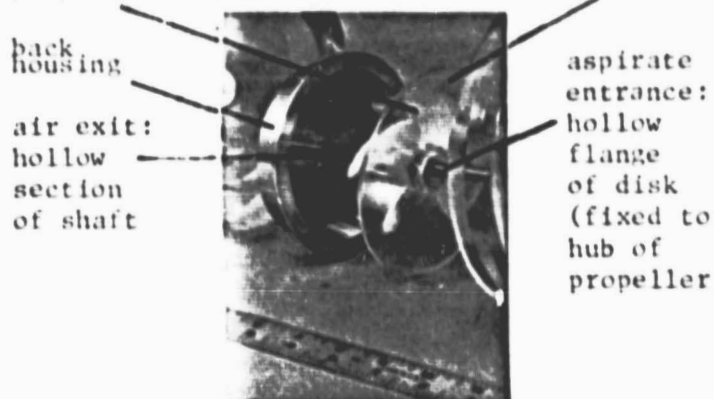
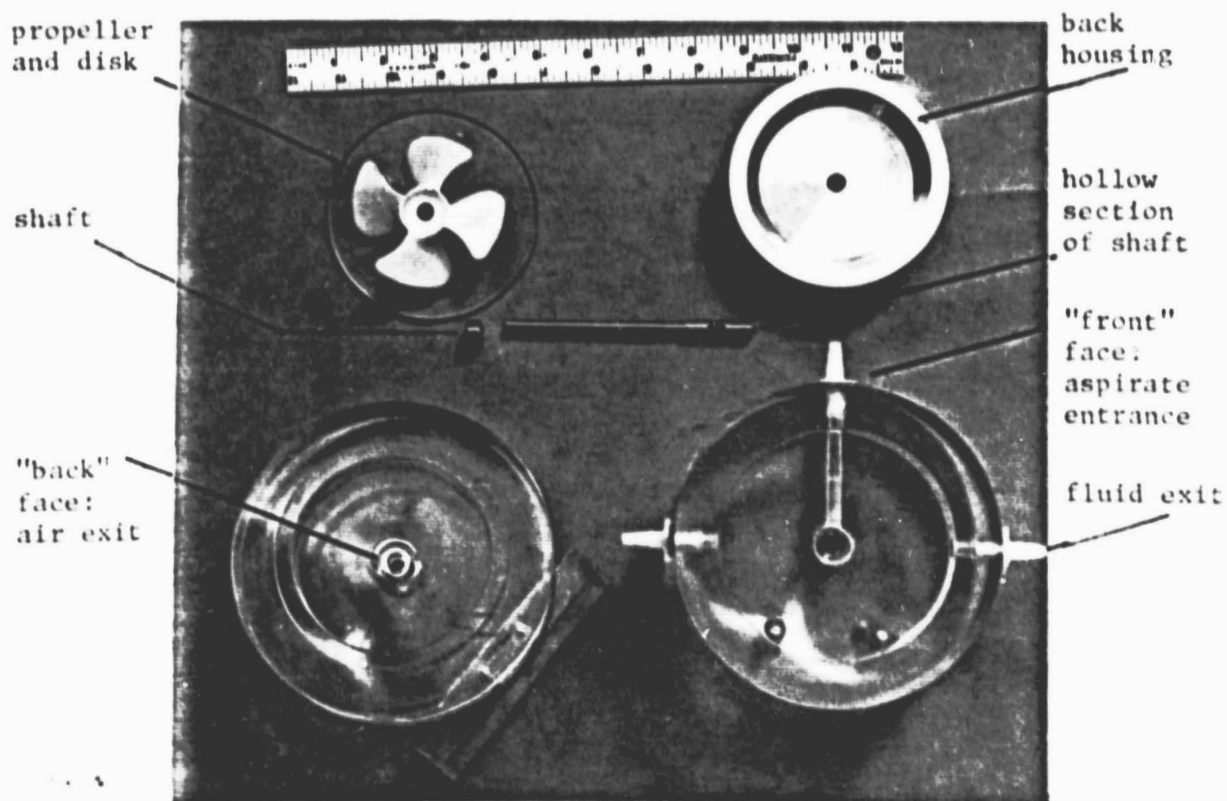


Figure 26: Full disassembly of rotating chamber



## **TESTING THE APPARATUS:PRELIMINARY RESULTS**

### **LABORATORY TESTING, 1G**

#### **Zero-G Surgical Module**

The module assembles and disassembles in an entirely satisfactory manner. The electrical system functions as desired. All equipment attaches as desired. There is easy access to the control switches for electrocautery and suction. The restraint system is easy to enter and exit. The operating and instrument retention surfaces are in very acceptable proximity when the surgeon is standing in the restraint system. The adjustable heights of operating surface and waist belt permit maintenance of acceptable relative positions of the working surfaces for persons whose heights range from 5 feet 2 inches to 6 feet 3 inches. The instrument surfaces and drawers accommodate more instruments, suture, sponges, etc. than would be required to perform surgery upon a small anesthetized animal.

#### **Zero-G Suction (FAST SLING) Unit**

The unit assembles and disassembles in an entirely satisfactory manner. The electrical circuitry functions as desired. All components attach as desired.

Specific function of the fluid-air separator can best be divided into 3 phases: intake of aspirate (fluid, air, or both), separation of fluid from air, and collection of the fluid. Function of the first 2 phases has been excellent under all circumstances; the collection phase has encountered problems under special circumstances.

Transition from aspiration of air (system "open," with sucker tip not in contact with fluid) to aspiration of liquid (system "closed," with sucker tip immersed in fluid) is extremely brisk; this almost certainly relates to the relatively small chamber which must be evacuated of air before full negative pressure is experienced in the inlet tubing; this is a distinct advantage over the majority of medical suction units.

Separation of fluid from air is immediate and complete, with no fluid appearing on the distal side of the propeller unless the chamber becomes overloaded due to fault in the collection circuit (to be described). This separation occurs no matter what the up-down orientation of the chamber: When the port for evacuation of air from the chamber is "down" in one-G, this constitutes a more rigorous test of the separator principle than does operation in any attitude in zero-G.

Movement of fluid from the perimeter of the rotating chamber, through the one-way valves, into the collection bags, is rapid, without passage of air into the collection bags, and without return of fluid toward the chamber, under most circumstances. A



condition which can thwart sufficiently rapid collection is intermittent or partial obstruction of the outflow tubing between the chamber and the collection bags, coupled with unusually steady fluid uptake. An example is the following set of circumstances: A partial kink may occur in the outflow tubing to one of the 2 collection bags, while the other outflow tube is clamped to permit changing that collection bag. At the same time, the sucker tubing is held underwater, so that a steady stream of fluid, without mixture with air, is being aspirated into the separator chamber. When the rate at which fluid (without air) is entering the chamber exceeds the rate at which it is possible for fluid to exit into the collecting system, then, despite the centrifugal force attempting to move fluid to the periphery, the net accumulation in the chamber will force fluid toward the port at the hub at which air exits to pump. When fluid reaches the hub, it is aspirated into the line going to the pump. (For purposes of testing, a very small "drop chamber" was interposed between the chamber exit and the pump.) It should be noted that, relative to most medical suction applications, particularly surgical suction, this is a relatively unusual set of circumstances, because due to obvious limitations in volumes of physiologic fluids at any point in time, it is uncommon to have to continuously aspirate a large quantity of fluid with which no air is mixed.

A partial correction to the collection problem has been effected by enlarging the diameter of the outflow ports to the collection bag tubing, and by using very low resistance one-way valves.

## **FLIGHT TESTING, ZERO-G**

### **General**

Prior to completion of the surgical module, 3 flights were made by the principal investigator, to become familiar with zero-G flight in the KC-135 and to perform minor surgical tasks using a pilot's knee board as an instrument retention surface. Upon completion of the module, it was hoped that up to 2 weeks of zero-G flying (up to 6 flights, up to 40 parabolas per flight) could be completed, on a "space available" basis, in connection with the Innovative Use of Space Station Program contract. Actual experience with the module was limited to 2 flights: delays introduced by other experimenters who were paying for the flights, and by aircraft mechanical failures, required an extension of contract (no cost) to accomplish the flying; once underway with flight testing, an unexpected objection by the coordinator of the Marshall Space Center investigators, apparently on "grounds of principle" not entirely clear to the JSC zero-G personnel, resulted in inability to obtain motion picture recording of the inflight activities and caused early removal of the surgical module.

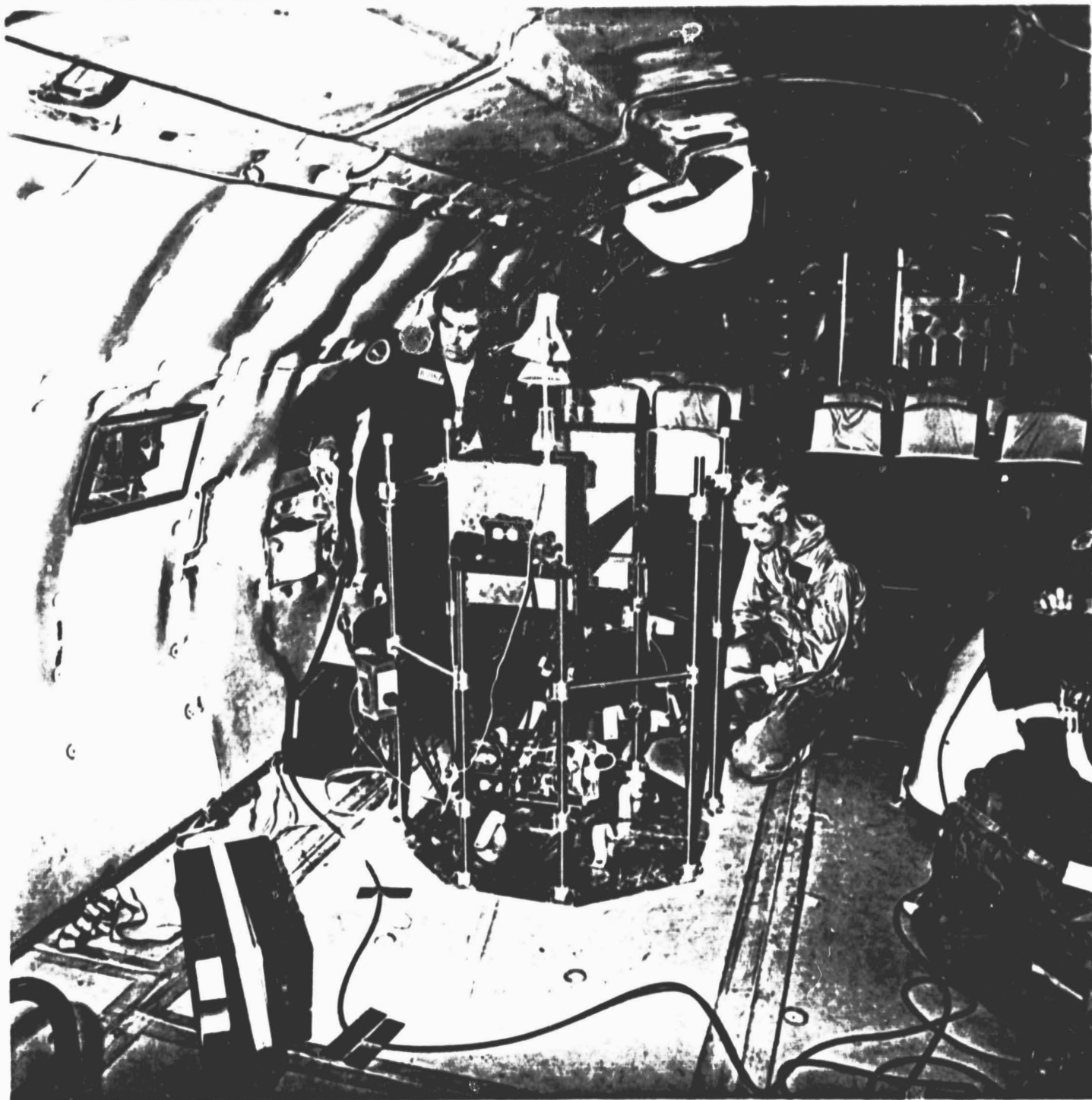
Nevertheless, the limited flight experience gained has been extremely valuable as regards validation of concepts to date and guidance of plans for further development and testing. The

principal investigator wishes to express deepest appreciation and thanks to Mr. Bob Williams of the Zero-G Office and Dr. James Logan of the JSC Flight Medicine Clinic for the enthusiastic and active support, cooperation, and advice they provided throughout the project; without this the flight testing would have been neither possible nor nearly as productive.

### **Zero-G Surgical Module and Surgical Techniques**

The apparatus is easy to load and assemble aboard the KC-135 aircraft (Figures 27-29). It mates well with the deck bolt attachment points, and with the aircraft electrical system.

Figure 27: Assembling the zero-G surgical module aboard the NASA KC-135 aircraft.





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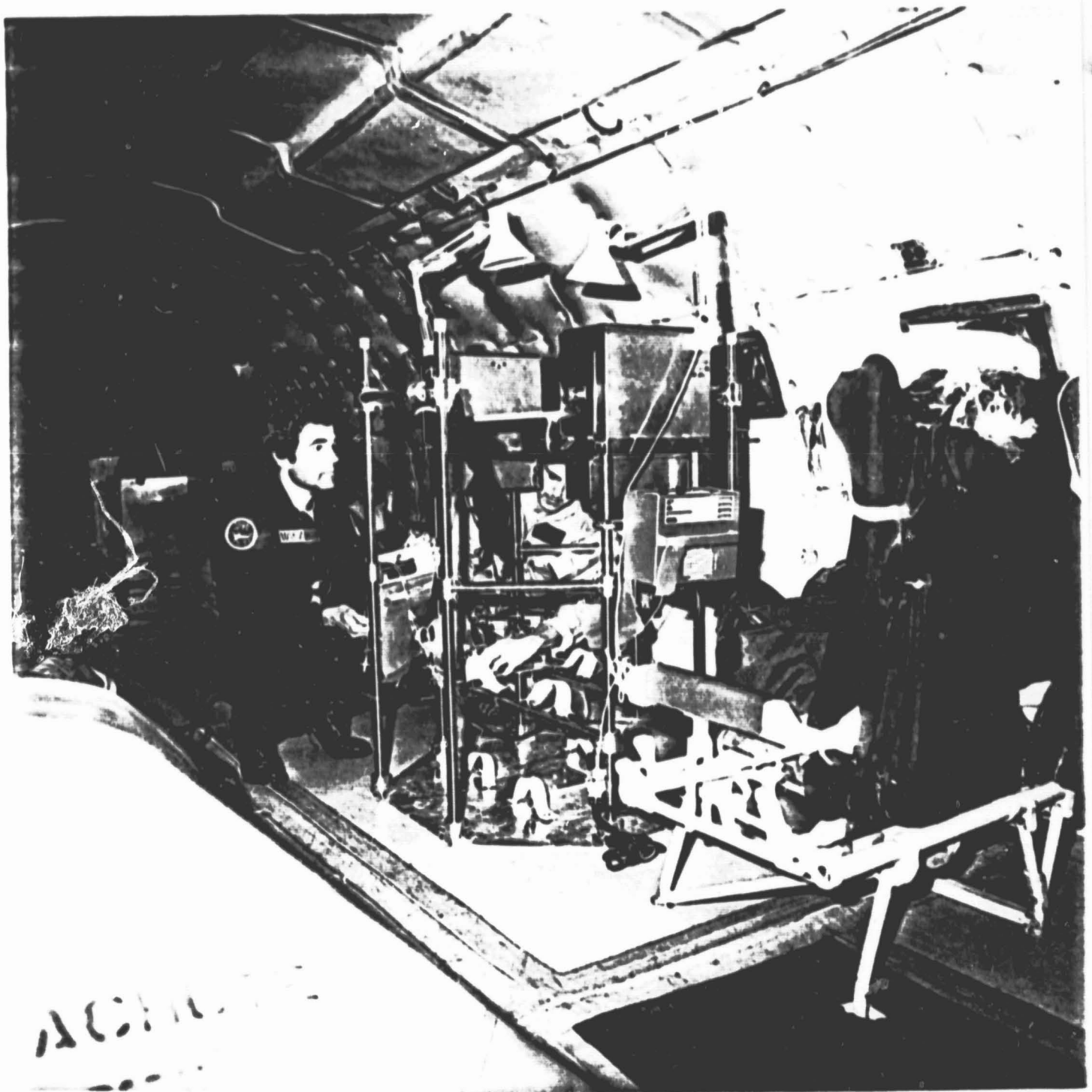
With the restraint system it is easy to maintain appropriate positions relative to the operating and instrument retention surfaces during zero-G maneuvers, including during transition to and from zero-G. The instrument retention surfaces function particularly well, with sufficient force of attraction to retain instruments even during slight negative-G surges, yet without excess force to the extent that picking up an instrument is an unnatural effort. Of particular

Figure 28: Assembling the zero-G surgical module aboard the NASA KC-135 aircraft



interest is the ability to release an instrument with a (low) velocity vector directed toward the retention surface, and observe the instrument drift onto the surface at constant speed to stick, in contrast, as on earth, to watching the instrument accelerate to the surface to bounce.

Figure 29: Assembling the zero-G surgical module aboard the NASA KC-135 aircraft



Several surgical tasks such as placing interrupted sutures in synthetic material and tying knots have been performed in order to assess influence of zero-G on manual dexterity (Figure 30). In general, there appears to be only minimal degradation of motor skill performance. In particular: (1) restraint at the feet and waist provides adequate stability for the necessary arm and hand movements; (2) the single most significant deterrent to smooth operating appears to be the slight but quite perceptible negative-G "bobbles" encountered a few times during each parabola (a phenomenon not present during constant zero-G); and (3) the single most significant aid to increasing zero-G operating skill will likely not be modification or addition to the restraint system, but, rather (as in operating in one-G), more practice operating in zero-G.

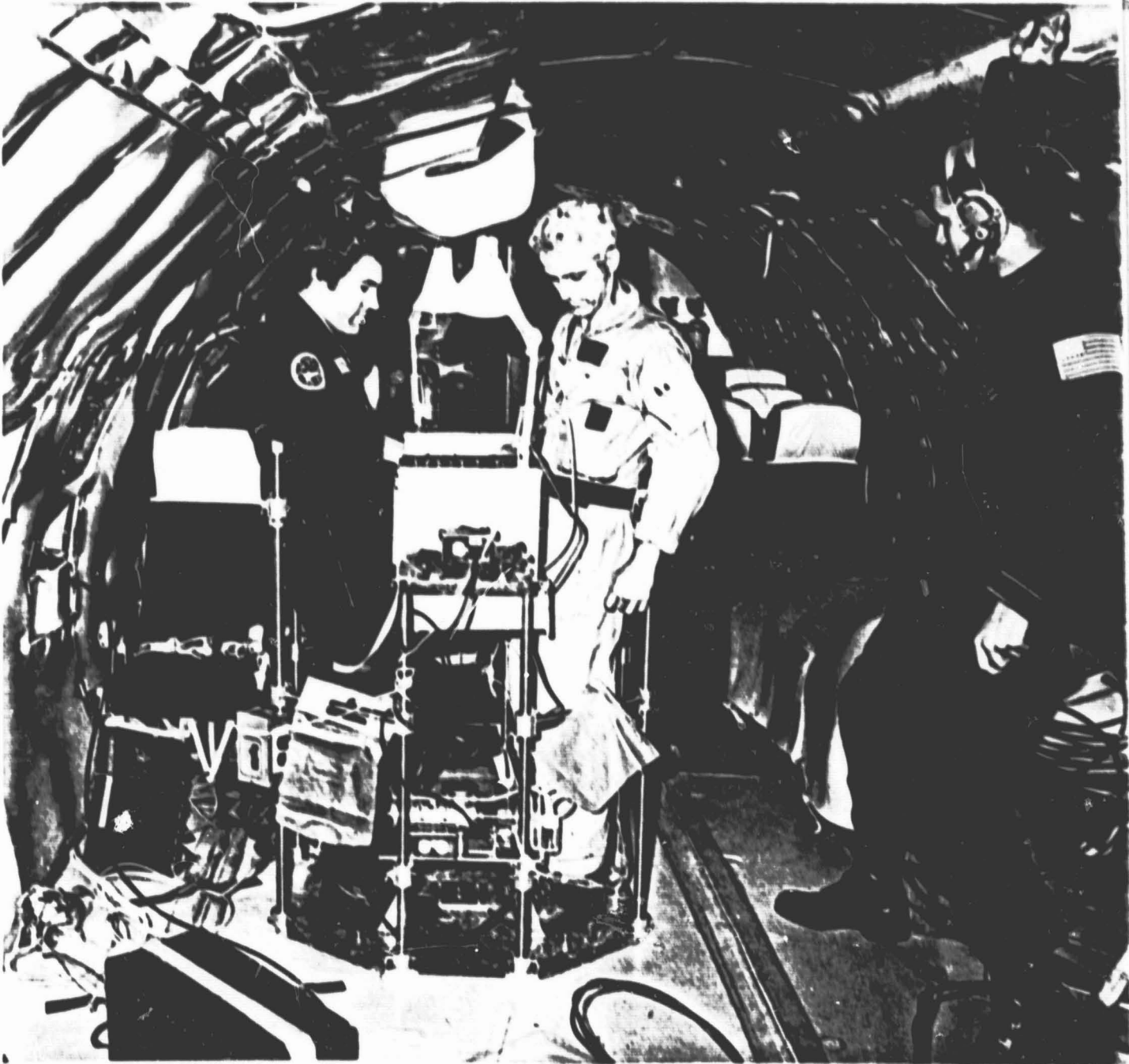
Figure 30: Surgical task performance during zero-G parabolic arc flight



### Surgical Suction (FAST SLING) Unit

The suction unit mates easily to the surgical module; the suction unit electrical system functions well on aircraft derived power. Test fluid (colored water) is easily contained in and accessed from a urine collection bag restrained on the operating surface. Air is easily mixed with the test fluid by intermittently uncovering a side hole in a sucker tip (Figure 31).

Figure 31: Evaluation of suction unit during zero-G parabolic arc flight



Function of the suction unit in zero-G is almost identical to that in one-G: Uptake of aspirate and separation of fluid from air is immediate and positive. Exit of fluid from the periphery of the chamber, and accumulation in the collection bags without return to the chamber, is satisfactory when the tubing between the chamber and exit ports and the collection bags has no kink or bend to constitute a relative obstruction. However, in zero-G, there appears to be some accentuation of the undesired consequences of a partial obstruction in the fluid outflow-collection circuit: When the sucker tip aspirates more fluid than air and the outflow lines are partially kinked, fluid is relatively quickly aspirated through the pump and aerosolized into the cabin. This effect may also be accentuated by inability of fluid to "fall to the bottom" of the collection bags under the influence of gravity, once passed the one-way outflow valves.

## **PRELIMINARY CONCLUSIONS**

1. In general, with appropriate mechanisms for body restraint of surgeons and for collection and containment of biologic fluids, it should be possible to perform surgery in zero-G using operating techniques and instruments not very dissimilar to those used in one-G.

2. In particular: Fixation of the surgeon at feet and waist should be satisfactory restraint, without need for additional arm or hand support beyond that provided by a tissue forcep. Use of a Fluid Air Suction Technique with Separation of Liquids Independent of Gravity (FAST SLING) unit, coupled with a local laminar air flow mechanism to be suggested, should provide satisfactory fluid management, without need to isolate the patient in or behind a transparent container.

3. The zero-G surgical module and the FAST SLING unit described in this report function well as prototype devices; they appear to represent appropriate devices with which to conduct additional experimentation to validate concepts and prompt further development.

4. Among things which are likely to improve ability to operate in zero-G, experience operating in zero-G is likely to be one of the most important. It is also the activity most likely to prompt ideas for addition of or modification to equipment. To maximize opportunity to develop techniques and identify equipment needs, it will be necessary to perform surgery on anesthetized animals in zero-G.

5. While imperfect in its simulation and inconvenient in its short time duration, parabolic arc flying in the NASA KC-135 aircraft represents the best laboratory available "on earth" in which to practice surgery in zero-G. The KC-135 aircraft is far superior to a swimming pool with regard to its ability to provide meaningful observations about techniques and apparatus that might actually be used in space station.

6. Funds specifically budgeted for zero-G flying should preclude objections to conducting experiments on a "space available" basis.

## **GENERAL RECOMMENDATIONS**

1. Efforts should be directed to development of apparatus and techniques which will permit surgery to be done in zero-G with minimum departure from procedures used on earth; in particular, with minimum interference with patient exposure and surgeon mobility.

2. The fluid collection component of the FAST SLING unit should be modified slightly to facilitate easier outflow from the separator chamber.

3. In the KC-135 aircraft during parabolic arc zero-G maneuvers, there should be further flight testing of the zero-G surgical module and the FAST SLING suction unit, to prepare the apparatus and experimental team for performance of surgery on small anesthetized animals in zero-G.

4. In the KC-135 aircraft during zero-G maneuvers, the surgical module and the FAST SLING unit should be used to perform surgery on animals of an appropriate species as regards public acceptability in NASA's view. Appropriate procedures might include central venous catheterization, tube thoracostomy, diagnostic peritoneal lavage, exploratory celiotomy, appendectomy, bowel resection, splenectomy. Careful film recording should be performed for later analysis.

5. NASA RTOP money should be identified specifically for these activities, so that the project can be viewed by other zero-G experimenters as paying its way.

6. When these goals are accomplished, additional problems discovered, and solutions evolved, a derivative of the zero-G surgical module should be flown in orbit. As suggested in Part I of the report on the System for the Management of Trauma and Emergency Surgery in Space, a dedicated clinical medicine spacelab mission would be an ideal shuttle launch on which to include a project to validate apparatus and techniques for surgery in zero-G.

ATTACHMENT A: Clinicians and Bioengineers Attending Space Surgery Conceptualization  
and Planning Conference, Clear Lake City, Texas, 20 and 21 July 1983

Bruce Browner, M.D.  
Associate Professor, Orthopedic Surgery  
University of Texas

Yoram Ben-Menachem, M.D.  
Professor and Chairman  
Vascular Radiology  
University of Texas

Christopher Bryan-Brown, M.D.  
Professor, Anesthesiology  
University of Texas

Joseph N. Corriere, Jr., M.D.  
Professor and Chairman  
Division of Urology,  
University of Texas

R. A. Cowley, M.D.  
Professor of Surgery and Director,  
Maryland Institute for Emergency Medical  
Services Systems, University of Maryland,  
Baltimore  
President, American Trauma Society

James H. Duke, M.D.  
Professor of Surgery  
University of Texas  
Medical Director, Life Flight,  
Hermann Hospital, Houston

Timothy C. Flynn, M.D.  
Assistant Professor of Surgery  
University of Texas  
(Former Antarctica Navy Medical Officer)

Joseph C. Gabel, M.D.  
Professor and Chairman  
Dept. of Anesthesiology  
University of Texas

Reed M. Gardner, Ph.D.  
Professor of Medical Biophysics and  
Computing, University of Utah,  
Salt Lake City

John R. Harris, M.D.  
Professor and Chairman  
Department of Radiology  
University of Texas

Bruce A. Houtchens, M.D.  
Associate Professor of Surgery  
University of Texas

Jiri Janata, Ph.D.  
Professor and Chairman  
Department of Biengineering,  
University of Utah  
Salt Lake City

James W. Justice, M.D.  
Indian Health Service Research  
and Development,  
Tucson, Arizona

Ernst Knobil, M.D.  
Dean, University of Texas

James S. Logan, M.D.  
Chief, Flight Medicine Clinic  
NASA Johnson Space Center  
Houston, Texas

Kenneth L. Mattox, M.D.  
Associate Professor of Surgery  
Baylor College of Medicine,  
Director, Emergency Services,  
Ben Taub General Hospital,  
Houston, Texas

Michael E. Miner, M.D.  
Acting Chief, Neurosurgery  
University of Texas

Frank G. Moody, M.D.  
Professor and Chairman  
Department of Surgery  
University of Texas

William Shoemaker, M.D.  
Professor of Surgery and Director,  
Surgical Intensive Care,  
Harbor General Hospital, Torrance,  
Editor, Critical Care Medicine

Donald Trunkey, M.D.  
Professor and Chairman  
Department of Surgery  
San Francisco General Hospital  
Chairman, Committee on Trauma,  
American College of Surgeons

James M. Vanderploeg, M.D.  
Chief, Flight Medicine  
NASA Johnson Space Center  
Houston, Texas

Glenn D. Warden, M.D.  
Associate Professor of Surgery  
University of Utah, Salt Lake City  
Director, Intermountain Burn Unit  
Codirector, Intermountain Trauma  
Complex



Conceptualization and Planning symposium:

SYSTEM FOR THE MANAGEMENT OF TRAUMA AND  
EMERGENCY SURGERY IN SPACE

A component of NASA'S  
Innovative Utilization of the Space Station Program

Lunar and Planetary Institute, and Johnson Space Center;  
20 and 21 July 1983

AGENDA:

Wednesday, 20 July:

0815-0830: Assemble at Lunar and Planetary Institute, (from the Hilton, walk 1/4 mile east, or ask for courtesy van transportation)

0830 Welcoming comments  
James M. Vanderploeg, M.D.  
Chief, Medical Operations Branch  
Johnson Space Center

Frank Moody, M.D.  
Professor and Chairman  
Department of Surgery,  
University of Texas, Houston

Bruce Houtchens, M.D.  
Associate Professor of Surgery  
University of Texas, Houston

The NASA perspective:

0845: Mini review, aerospace physiology:  
James M. Vanderploeg, M.D.

0915: Primer, operational medicine:  
James M. Vanderploeg, M.D.

0945: NASA concepts to date, development of space  
station health maintenance facility:  
James S. Logan, M.D.  
Chief, Flight Medicine Clinic  
Johnson Space Center

1015: Break

2

The university consultant's perspective:  
1030:

5-10 minute synopses directed to identification and consideration of: (1) specific emergency surgical problems likely to be encountered; (2) anticipated difficulties in managing these problems related to the unusual environment and limited resources; (3) those onboard and remote assistance capabilities which would be most helpful (i.e., the problem as seen from the viewpoint of a surgeon on board and a terrestrial consultant); and (4) how preparation to evaluate and manage specific events should be influenced by probability versus consequence of occurrence, costs of preparation versus non-preparation, and (if applicable) risks to rescuers and health workers.

Moderator's overview, initial evaluation and management of the trauma patient:

Bruce Houtchens, M.D.

Anticipated frequencies of occurrence of particular injuries and surgical emergencies: The Antarctic and submarine experiences:

1045-1100

Timothy C. Flynn, M.D.  
Assistant Professor of Surgery  
University of Texas, Houston  
(Former Antarctica Navy medical officer)

1100-1115

Head injuries and neurological disorders:

Michael E. Miner, M.D.  
Chief, Neurosurgery, University of  
Texas, Houston

1115-1130

Chest injuries and cardiac disease:

R. Adams Cowley, M.D.  
Professor of Surgery and Director,  
Maryland Institute for Emergency Medical  
Services Systems, University of  
Maryland, Baltimore  
President, American Trauma Society

Kenneth L. Mattox, M.D.  
Associate Professor of Surgery,  
Baylor College of Medicine, Houston  
Director, Emergency Services,  
Ben Taub General Hospital, Houston

1130-1200

Abdominal injuries and gastrointestinal dysfunction:

Donald Trunkey, M.D.  
Professor and Chairman,  
Department of Surgery  
San Francisco General Hospital  
Chairman, Committee on Trauma,  
American College of Surgeons  
Bruce Houtchens, M.D.

1200-1215      Pelvic injuries and urologic disorders:  
                  Joseph N. Corriere, Jr., M.D.  
                  Professor and Chairman,  
                  Division of Urology,  
                  University of Texas, Houston

1215-1230      Orthopedic injuries and musculoskeletal  
                  dysfunction:  
                  Bruce Browner, M.D.  
                  Associate Professor, Orthopedic Surgery  
                  University of Texas, Houston

                 Vascular injuries and perfusion defects:  
                  Donald Trunkey, M.D.  
                  Timothy C. Flynn, M.D.

1245-1315      Lunch, Lunar and Planetary Institute  
                  Background, Lunar and Planetary Institute  
                  John Harris, Jack Sevier  
                  University Space Research Associates

1315-1345      Diagnostic radiologic capabilities: what  
                  are minimum requirements and reasonable  
                  goals?  
                  John H. Harris, Jr.  
                  Professor and Chairman  
                  Department of Radiology  
                  Yorum Ben-Menachem  
                  Professor and Chairman  
                  Division of Vascular Radiology  
                  University of Texas, Houston

1345-1430      Thermal, electric, and other soft tissue  
                  injuries:  
                  Glenn D. Warden, M.D.  
                  Associate Professor of Surgery,  
                  University of Utah, Salt Lake City  
                  Director, Intermountain Burn Unit,  
                  Codirector, Intermountain Trauma  
                  Complex.

1430-1600      Tour, Johnson Space Center facilities  
                  James Logan, M.D. and NASA staff

1600-1700      Press conference, JSC public information  
                  center (room 135)

1700            Assemble, Hilton lounge (happy hour):  
                  Recap of days activities, charges for  
                  following day's planning sessions.  
                  Frank Moody, M.D.  
                  Bruce Houtchens, M.D.  
                  James Logan, M.D.

1900            Dinner in the Hilton dining room (over the  
                  yacht harbor):  
                  Frank Moody, M.D. and the University  
                  of Texas Department of Surgery, hosts.

Thursday, 21 July

0800            Assemble at Lunar and Planetary Sciences Institute

0800-0815            Ability (and propriety of attempting) to provide short or long term intensive care with limited space and resources:  
Christopher Bryan-Brown, M.D.  
Professor of Anesthesiology and Surgery,  
University of Texas, Houston  
Director, Surgical Intensive Care,

0815-0845            Monitoring of the critically ill or injured patient: Which variables might be most appropriate in the presence of limited resources?  
William Shoemaker, M.D.  
Professor of Surgery and Director, Surgical Intensive Care,  
Harbor General Hospital, Torrance, CA.  
Editor, Critical Care Medicine

0845-0830            Selecting or developing optimum monitoring and support equipment to meet constraints of limited space, weight, and power:  
Jiri Janata, Ph.D.  
Professor and Chairman,  
Department of Bioengineering,  
University of Utah, Salt Lake City

0930-1000            Organization, recording and transmission of patient data for optimum decision making, both onboard and remotely:  
Reed M. Gardner, Ph.D.,  
Professor of Medical Biophysics and Computing, University of Utah,  
Salt Lake City

1000-1015            Coffee Break

1015-1045            Medical apparatus development: Space shuttle medical kit, rehydratable IV infusion system using fuel cell produced water, mask ventilation system, zero G CPR restraint system.  
James Logan, M.D. and NASA staff

1045-1115            Zero G surgical technique development (depending on progress to date):  
Bruce Houtchens, M.D.  
James Logan, M.D.

1115-1145            Experience to date with remote medical consultation based on transmission of data  
James W. Justice, M.D.  
Indian Health Service Research and Development, Tucson, Arizona

1145-1230

Round table response, discussion:  
University consultants, NASA staff

Should and can we establish a national  
emergency medical resource network and  
consultation system? \*

What are the medical benefits and the  
political pitfalls?

How can NASA tap the University medical  
community?

Will selected university surgery  
departments need to consider the issue  
of special training in "space surgery?"

David R. Boyd, M.D.C.M.  
R. Adams Cowley, M.D.  
Ken Mattox, M.D.  
Frank Moody, M.D.  
Donald Trunkey, M.D.

1230-1300

Assumption of responsibilities and  
development of an agenda for effecting a  
consensus plan of action.

1300

Adjourn.

# SYSTEM FOR THE MANAGEMENT OF TRAUMA AND EMERGENCY SURGERY IN SPACE

## OUTLINE FOR PRESENTATION/SUMMARY REPORT OF THE UNIVERSITY CONSULTANTS' PERSPECTIVIES

### Area Assigned:

1. Specific clinical (engineering) problems likely to be encountered in this area:
2. Anticipated difficulties in managing those problems, related to the unusual environment and limited resources likely to be associated with a first generation space station:
3. Those on board and remote problem solving and data collection/transmission capabilities which would be most helpful, as seen from the viewpoint of:
  - a. A surgeon onboard:
  - b. A terrestrially based clinical specialty consultant:
4. How preparation to evaluate and manage problems onboard and remotely should be influenced by:
  - a. Probability of occurrence
  - b. Medical consequence of occurrence
  - c. Cost of preparation (equipment weight, size, electrical power, dollars)
  - d. Cost of lack of preparation (dollars to effect an unscheduled rescue; political consequences of resultant M + M, operational consequences of loss of key crew members)
  - e. Potential risks to rescuers and health workers (if applicable)
5. General comments:

**Proposals Selected for the Innovative Utilization  
of the Space Station Program**

- Dr. Thomas J. Ahrens, California Institute of Technology**  
Orbiting Dynamic Compression Laboratory
- Dr. Jeffrey R. Alberts, Star Enterprises**  
Mammalian Development and Reproduction During and Subsequent to Null Gravity Conditions
- Dr. Robert S. Bandurski, Michigan State University**  
The Alpha Helix Concept
- Dr. Alan N. Bunner, Perkin-Elmer Corporation**  
Optical Coating in Space
- Dr. Lewis M. Duncan, Los Alamos National Laboratory**  
Study of Requirements for a Space Station Incoherent Scatter Radar
- Mr. James C. Fox, KMS Fusion, Inc.**  
Study of Robotics Systems Applications to the Space Station Program
- Dr. Ronald Greeley, Arizona State University**  
Feasibility Study to Conduct Windblown Sediment Transport Experiments Aboard a Space Station
- Professor Herman H. Hobbs, George Washington University**  
Terrestrial Whisker Growth Experiments which Anticipate Some Special Effects of a Space Station Experiment
- Dr. Bruce A. Houtchens, University of Texas Health Science Center**  
System for the Management of Trauma and Emergency Surgery in Space
- Dr. David G. Koch, The Center for Astrophysics**  
A Large Area Gamma-Ray Imaging Telescope System
- Dr. Koichi Masubuchi, Massachusetts Institute of Technology**  
Feasibility of Remotely Manipulated Welding in Space, A Step in the Development of Novel Joining Technologies
- Dr. F. Curtis Michel, William Marsh Rice University**  
Analog Magnetospheric Physics Simulations from a Space Station
- Dr. Gregory A. Nelson, Jet Propulsion Laboratory**  
Novel Approach to the Study of Developmental Biology in Space

(Continued next page)

- Mr. James S. Pridgeon  
The Artistic Potential of the Space Station Program
- Dr. Robert Stachnik, The Center for Astrophysics  
A Study of a Space-Station-Associated Multiple Spacecraft Michelson  
Spatial Interferometer
- Dr. Robert E. Turner, Science Applications, Inc.  
A Proposal for the Measurement of the Atmospheric Aerosol Content from  
a Space Station
- Mr. Donn C. Walklet, Terra Mar  
Alternative Strategies for Space Station Financing
- Dr. William J. Webster, Jr., Goddard Space Flight Center  
Measurement of Earth's Magnetic Field at High and Extremely Low  
Altitude Using Space Station-Controlled Free-Flyers